Know-how for Horticulture™

Commercial implementation of innovative carrot production technologies

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Field Fresh Tasmania

Project Number: VG01095

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This report is published by Horticulture Australia Ltd to pass on information concerning horticultural research and development undertaken for the vegetable industry.

The research contained in this report was funded by Horticulture Australia Ltd with the financial support of Field Fresh Tasmania.

ISBN 0 7341 1083 9

Published and distributed by:
Horticultural Australia Ltd
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50 Carrington Street
Sydney NSW 2000
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Commercial Implementation of Innovative Carrot Production Technologies

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The purpose of this report is report on efforts undertaken by Field Fresh Tasmania to develop innovative carrot production technologies (based on recent scientific advances) to increase the proportion of carrots that reach current marketing specifications. *Any recommendations contained in this publication do not necessarily represent current Horticulture Australia policy. No person should act on the basis of the content of this publication, whether as to matters of fact or opinion or other content, without first obtaining specific, independent professional advice in respect of the matters set out in this publication.*

Acknowledgements

The investigators gratefully recognise the funding providing by Horticulture Australia Ltd and Webster Ltd, and the collaborative support provided by the University of Tasmania. We would also like to acknowledge the invaluable contribution of Brian Walker in the development and modification of the carrot top trimming machinery. Thanks also to Peter Forbes for his work in the field.

Report authored by Dr Alistair Gracie and Mark Boersma.

8 March 2005

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Media Summary

Tasmania is a major producer of high quality fresh carrots for niche export markets that demand blemish free carrots of a specific size and shape. Even though the total yield of carrot roots produced in Tasmania is high, commonly 30% of a crop will fall outside of the market specifications. Carrot root splitting, twisting, and a high variation in carrot root sizes within a crop are major contributors to this loss.

This project has focussed in two main areas; technologies to address carrot root splitting and the minimisation of carrot shape defects and size variation through the manipulation of plant spacing arrangements at sowing.

Previous research has indicated that trimming carrot leaf canopies prior to harvest can alleviate root splitting. Equipment to trim foliage both horizontally and vertically through the canopy was designed and developed as part of this project.

Leaf trimming provided some benefit, but its effectiveness appeared to be influenced by environmental variables, in particular soil moisture. The greatest reduction in splitting following leaf trimming occurred where both soil moisture and the tendency for roots to split were high. Generally the more leaf material removed, the more effective the treatment.   The time of day the treatment was applied did not reduce the effect of trimming, which was observed to reduce the incidence of splitting for up to 10-12 days after treatment.

Previous research has also provided some evidence that improving the evenness of plant spacing may reduce the level of shape defects and size variation.

An analysis of in row plant distribution revealed that the current in-row spacing was extremely variable and the proportion of seed falling within the target spacing range was lower than that recorded for other vegetable crops. Sowing of larger seeds to improve seed drill accuracy generally increased the proportion falling within the target range, but only slightly. Greater improvements to planting precision are required.

The proportion of carrots falling within a medium size class was improved by planting single rows rather than multiple double rows on a bed; however, there was trade off associated with reduced gross yield due to the lower number of plants per square metre.

Misshapen taproots were a major cause of reduced pack out, especially for the longer Nantes varieties. Carrots varieties with longer taproots were more likely to fork.

Technical Summary

The volume of carrots produced in Australia for domestic and export markets has been steadily increasing over the past decade. Tasmania is a major producer of high quality fresh carrots for niche export markets that demand carrots of specific size, shape and blemish free status. Even though the total yield of carrot roots produced in Tasmania is high, a substantial proportion fall below market specifications and are sold for a greatly reduced price or discarded. The major causes of reduced marketable yield are taproot splitting, taproot shape aberrations, and high variability in taproot sizes. This project sought to examine and develop innovative commercial technologies to minimise losses and increase the proportion of premium export grade carrots cultivated. The study was divided into two main themes; technologies to abate carrot splitting and physical damage, and minimising carrot shape defects and size variation through manipulation of plant spatial arrangement.

Longitudinal tissue fracture (splitting) affects approximately 6% of carrots produced. Splitting can occur during the growth and development of the crop (growth splitting) or while harvesting and handling (harvest splitting). The use of a modified handheld penetrometer provided a quick and reliable way of quantifying the splitting susceptibility of a population of carrots.

The strategic use of leaf trimming treatments to abate splitting during the early morning harvest period, when splitting susceptibility is at its highest, was investigated. The leaf trimming application provided some benefit, but its effectiveness appeared to be influenced by climatic variables, notably soil moisture level. The greatest reduction in splitting susceptibility following leaf trimming occurred in conditions where splitting susceptibility and soil moisture content were high. The time of day leaf trimming was applied did not affect the magnitude of the reduction in splitting propensity the following day. Generally, the more leaf material severed the greater the reduction in splitting susceptibility. In crops where leaf trimming reduced splitting, complete defoliation significantly decreased splitting propensity for a 12 day duration, while horizontal and vertical trimming reduced splitting propensity for a 10 day period compared with untreated control plants.

Custom designed machinery for applying vertical and horizontal trimming to commercial crops was successfully employed. The trimming treatment left sufficient sturdy petiole material to permit harvesting by top pulling.

Given the success of complete defoliation in reducing splitting propensity an alternative harvesting technique besides top pulling was investigated for harvesting defoliated carrots. Shear lifting, a technique used in processing carrot production, was assessed however the method caused substantial physical damage to the surface of the carrot.

Undercutting taproots the day prior to harvesting using a root pruning shear set at 300mm depth was successfully implemented to reduce splitting susceptibility. Unfortunately the process of undercutting caused leaves to wilt making the carrots difficult to harvest using a conventional top-pulling harvester. Adjustments were made to the undercutting bar to fine-tune the severity of disturbance to the fibrous roots and thus leaf wilting.

Growth splitting was monitored in crops at sites of high and low soil moisture. Growth splitting occurred mainly in the later stages of crop development and the incidence was generally higher when soil moisture content was high.

Previous research provided some evidence that improving the evenness of plant spacing may reduce the level of shape defects and size variation. This work sought to extend these findings by manipulating evenness of spacing through seed grading and plant spatial arrangement. Spacing Index analyses revealed that the current intra-row spacing was extremely variable and the proportion falling within the target spacing range was lower than that recorded for other vegetable crops. Sowing large seeds generally increased the proportion falling within the target range, but only slightly. Greater improvements to planting precision are required.

The proportion of carrots falling within a medium size class was improved by planting single rows rather than multiple double rows on a bed; however, there was trade off associated with reduced gross yield due to the lower stand density.

Misshapen taproots were a major cause of reduced pack out, especially for the longer Nantes varieties. Carrots varieties with longer taproots were more likely to fork.

An objective method of assessing the degree of rounding at the carrot root tip, a parameter used to assess crop maturity was developed. Actual carrot tip volumes were initially compared to theoretical tip volumes using different geometrical shapes, however this technique was not able to adequately distinguish between tapered and rounded carrot tips. A photographic key was developed and successfully incorporated into a commercial harvest program.

Introduction

Major challenges to carrot quality improvement

The Australian carrot industry has been expanding steadily over the last decade with total production increasing from 169,000 tonnes in 1992 to 285,000 tonnes in 2002 (FAO, 2003). This current level of production makes carrots one of the most important vegetable crops produced in Australia.

Carrot production in Tasmania has also increased appreciably in recent years. In 1999-2000, carrot production was estimated at 35,000 tonnes, an increase of 67% on the 1995-96 level of 21,000 tonnes (Australian Bureau of Statistics). The production of fresh carrots for domestic and international markets is a major component of Tasmania's carrot industry. The future for carrot export is optimistic and there are expectations that the industry in Tasmania will continue increase in size.

The cool temperate climate and fertile soils in Tasmania are ideal for the production of carrots and yields in excess of 100 tonnes/Ha are occasionally achieved, though yields between 60 to 70 tonnes/Ha are more common. While the total root biomass per unit area is high, only approximately 50% to 80% of all carrots cultivated are of suitable quality for retailing as premium Class 1 fresh product, referred to as pack out. The major causes for Class 1 rejection includes, longitudinal fracture of the tissue (splitting), misshapen carrots, carrots smaller or larger than market specification, and blemishes on the surface of the root caused by physical damage and diseases. In order to be more competitive in the international markets there is a need for increased production efficiencies. Increased efficiencies would translate into greater fiscal returns to both the grower and packing companies and ensure the ongoing success of the industry.

In most regions of the world carrots are cultivated on soils of light texture. This contrasts to production in Tasmania where carrots are cultivated primarily on soils of high clay content. It is in the context of this production system that this project was initiated to develop commercial technologies to increase the proportion of premium grade carrots cultivated. A study undertaken from 1998 to 2001 examined the major non-pathogenic factors causing reduced pack out and elucidated some of the factors underpinning their expression; this included both taproot splitting, misshapenness, and size variability (Brown and Gracie, 2000). The aim of this project was to extend these recent advances and develop commercial technologies based on the recommendations. This project is divided into two main themes; development of technologies to abate carrot splitting and physical damage, and minimising carrot shape defects and size variation through manipulation of seed placement, row arrangement and stand density.

Technologies to abate carrot splitting and physical damage

Carrot splitting is characterised by tissue fracture along the length of the carrot taproot. The length of the fractures ranges from a few centimetres to the entire length of the taproot. Carrots split either during the growth of the crop (referred to as growth splitting) or during the harvesting and handling operations (referred to as harvest splitting). Apart from being unsightly, splitting exposes the inner flesh of carrots to the soil and therefore likely pathogen contamination and spoilage. For these reasons split carrots are manually culled from harvesters and packing lines. The incidence of splitting varies between crops and seasons, and typically effects from 1 or 2% up to 20% of carrots. Data collected by Field Fresh Tasmania revealed that on average 6.2% of carrots produced in Tasmania for the fresh market were rejected due to splitting (growth plus harvest splits) (Table 1).

Table 1. Non Class 1 Assessments Major Physical Faults (in no particular order)

	Season			
Faults	1998/99	1999/00	2000/01	***Average***
Growth splits	2.6%	1.3%	1.4%	***1.8%***
Harvest splits	5.7%	3.6%	3.8%	***4.4%***
Side damage	1.3%	1.1%	1.0%	***1.1%***
Shoulder damage	0.7%	0.9%	0.7%	***0.8%***
Broken	3.6%	3.3%	3.2%	***3.4%***
Misshapen	7.5%	5.4%	5.3%	***6.1%***
Total	***21.4%***	***15.6%***	***15.2%***	

Gracie (2002) was successful at advancing the understanding of the physiological mechanism underpinning carrot splitting. From his studies he was able to demonstrate that carrots fluctuate diurnally in their tendency to split. More specifically, carrots were most susceptible to harvest splitting at sunrise, and decreased in ease of splitting during the middle of the day, before increasing again during the evening. While it is possible to reduce the incidence of splitting by restricting harvesting operations to a period when splitting susceptibility is low (e.g. between 10am and 3pm), it is not an efficient use of harvesting equipment and only addresses the issue of harvest splitting and not growth splitting.

A further series of trials were undertaken by Gracie (2002) to test the hypothesis that trimming carrot leaves the day prior to, or a number of days prior to harvesting reduces both harvest and growth splitting. The results obtained from the trials showed that harvest splitting was significantly reduced when leaf trimming was applied the day prior to harvesting, however the effectiveness of leaf trimming decreased with an increasing delay between treatment application and time of harvesting. Growth splitting occurs mainly in the later stages of crop development and trimming the foliage a week prior to harvest significantly reduced the incidence of growth splits in crops where the disorder was expressed (Gracie, 2002). The work by Gracie (2002) involved small plot trials and contained only a limited data set. No other published research has been carried out on the commercial potential of these novel strategies. The aim of this current research project was to extend these preliminary findings and undertake additional research based on the recommendations of the author. This includes, examining time of day leaf trimming is applied, and amount and type of foliage removed. From this work the development of innovative technologies for commercial implementation were evaluated.

Minimising carrot shape defects and size variation

In addition to sensory qualities such as taste and smell, taproot size, shape and appearance are all important marketing parameters. Carrot harvest maturity is generally based on taproot dimensions of diameter, length and the degree of rounding of the root tip and thus agronomic and environmental factors influencing these attributes have received some attention in the literature (Thompson, 1969; Dowker et al, 1976a; Umiel et al., 1992; Howarth et al., 1992; Bradely et al., 1967), however issues such as taproot shape aberrations have received very little even though it is a major factor causing reduced pack out (Table 1). To the knowledge of the authors, it wasn’t until recently that an independent scientific report examining factors influencing carrot dimensions, shape defects variability in size in the current production systems in Tasmania (or Australia) were reported in the literature (Gracie, 2002). This project also sought to extend the preliminary data reported by Gracie (2002) showing that increased evenness of intra row seed spacing and low stand densities, resulted in reduced levels of carrots with shape defects. Possible ways of integrating these findings into the commercial production system are investigated. Strategies considered include manipulating seed placement, row arrangement and stand density.

Statistical analysis

In this study data were analysed using Statistical Analysis Software (SAS ver. 8.0, SAS Institute Inc. Cary, NC, USA 1999-2001). The following SAS procedures were used during the course of this project: PROC ANOVA for analysis of variance, PROC CORR for correlation, and PROC GLM and PROC REG for regression.

Data expressed as proportions were angularly transformed, using the arcsine transformation, when values ranged from between 0 and 0.3 and 0.8 and 1. Differences between treatment means were determined using Fishers LSD ($P=0.05$) when found to be significant ($P<0.05$) in the analysis of variance test.

Technologies to abate carrot splitting and physical damage

Trimming carrot leaves to reduce the susceptibility of carrots to splitting

Background

Carrot taproots are noted for the ease with which they fracture longitudinally, referred to as splitting. The splitting disorder episodically affects a large proportion of carrots within a crop and can occur during the crop growth and development or during harvesting and handling. While it is common for 6% of carrots in a crop to split, levels of splitting in excess of 20% have been reported in UK (McGarry, 1994), and Tasmania (Gracie, 2002). Hence carrot splitting represents a significant loss in potential earnings to both the carrot growers and packing companies. The need to manually remove split carrots, and subsequent loss in factory efficiency, are additional costs borne by the packing company.

Although this disorder is genetically linked (Michalik et al., 1997), a strong environmental interaction exists and hence large variance in incidence occurs within a single genotype cultivated in the same growing season and production region. This observation has led to numerous agronomic trials examining the effect of different fertiliser and irrigation regimes (McGarry, 1994; Sparrow et al., 1996; Bienz, 1965;). Although there is substantial evidence that excessive nitrogen applications exacerbate the splitting disorder (Bienz, 1965; Batra and Kalloo, 1990), to date, no single nutritional or irrigation regime have been reported to repeatedly abate carrot splitting and provide a feasible management tool to the carrot industry.

Also compromising the elimination of splitting through breeding programmes is the possibility the disorder is genetically linked with other desirable qualities such as texture and sweetness (Rubatzky et al., 1999). Thus the inability to fully manage the incidence of carrot splitting through current breeding programmes or agronomic manipulation has led to the most recent series of research into splitting to examine the underlying mechanism involved. The elucidation of the physiological processes underpinning carrot splitting has led to the suggestion of a number of integrated strategies over the last few years, however, these ideas require further commercial evaluation. This short review of carrot splitting details the physiological basis of splitting before highlighting some of the most recent promising strategies reported. This study further refines and tests these novel strategies at the commercial level.

Mechanism underpinning carrot splitting

The edible carrot taproot consists largely of two main parts; the phloem tissue (outer sheath of tissue) and the xylem core (inner core) (Figure 1). Typically a longitudinal fracture of taproots radially transects the periderm ('skin') and phloem tissue, stopping before reaching the xylem core and varies in length from a few centimetres to the entire length of the taproot. Detailed scanning electron microscope examination of a fracture surface clearly shows that the fractures are generated through cell wall breakage rather than the separation of cells (McGarry, 1995). This observation suggests that cell wall properties may be critical to the splitting susceptibility of taproots.

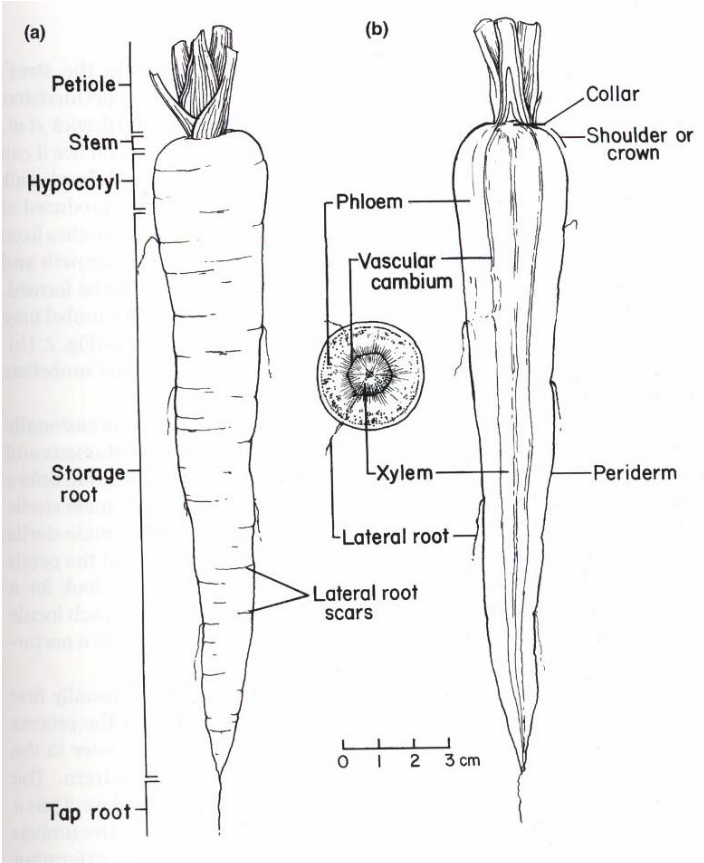


Figure 1. Anatomy of the carrot taproot. Illustration sourced from Rubatzky et al., 1999

Most of the published literature investigating the physiological basis of the carrot splitting disorder has been undertaken at Horticulture Research International (HRI) in the United Kingdom. From numerous environmental, developmental and genotypic studies the researchers at HRI were able to demonstrate that splitting was not linked to tissue fracture properties (tissue strength and fracture toughness), leading Hole et al. (1999) to conclude that the traditional method of selecting for tissue strength as a way of breeding for 'splitting resistance' may offer limited benefits. In addition to this it has also been reported that splitting was not linked to turgor pressure, the intra cellular hydrostatic pressure that provides the impetus for tissue expansion. However, the validity of the technique used to determine turgor has since been questioned (Gracie, 2002).

For a fracture to be initiated the internal forces must exceed the capacity of the tissue to withstand it. Since tissue fracture properties have not accounted for differences in splitting recorded in genotypic, developmental and environmental studies (Hole et al., 1999), the major factors controlling splitting must be associated with the magnitude of the internal pressures. The longitudinal alignment of the taproot fracture is consistent with the development of circumferential stress. Circumferential stress can be induced by intracellular hydrostatic pressure (turgor) and also gradients in tissue extensibility properties (elastic and plastic properties) across the taproot (Kokkoras, 1995; Sorenson and Harker, 2000). From work on splitting in apples, Skene (1980), was able to point out that for a gape to occur at the periphery of the fruit, cells close to the centre of the fruit must have greater extensibility than cells closer to the periphery. New cells in the carrot taproot are initiated at the vascular cambium while the more mature phloem cells are found with increasing distance from the cambium zone. Simple tests have shown that the inner xylem core is not under tensile stress (Hole *et al*, 1999) and therefore the driving force for splitting is most likely generated in the phloem tissue.

Development of partial defoliation treatment

There is mounting evidence that the impetus for splitting of the mature carrot taproot is derived from higher growth rates of the inner phloem tissue compared with tissue in the outer phloem zone. Recently synthesised carbohydrate is transported from the leaves down to the taproot through active transport sieve cells in the inner phloem tissue, becoming incorporated into insoluble material (most likely cell wall material) mainly in the inner zone. It was hypothesised by Gracie (2002) that the removal of the foliage from the plant would reduce carbohydrate synthesis and slow down growth of the inner phloem tissue, in turn reducing circumferential stress and thus carrot splitting. A number of small trials have been undertaken to test this hypothesis (Gracie, 2002). In the study undertaken by Gracie (2002) leaves were either trimmed vertically to remove all the older leaves, trimmed both vertically and horizontally, or left untreated. Where horizontal and vertical trimming was applied simultaneously, the treatment reduced both the radial growth of the taproot and splitting propensity when applied to mature plants the day prior to harvest.

In the research conducted by Gracie (2002) leaf trimming was applied at midday, as this time corresponded to the time of day when leaf water potential was at its lowest. It was assumed that the leaves stored recently synthesised assimilates as starch in the leaves during the daylight hours, which would be hydrolysed and transported down the taproot during the dark period when gradients in water potential favour this. If commercial cutting machines were to be developed a number of important questions need to be answered. First, is it essential that the leaf trimming be applied at midday for the treatment to be successful and what is the effect of trimming at other times of the day? Secondly, How much leaf removal is required for the treatment to be effective? And thirdly, how long do the benefits of leaf trimming last for? These questions are examined in a series of trials conducted in commercial crops prior to the development of possible mechanical technologies.

Method for measuring splitting susceptibility

A range of techniques have previously been employed by researchers to quantify how a treatment (or treatments) influences the splitting propensity of a population of carrots. The methods include; dropping carrots from a set height or a series of heights (Michalik et al., 1997); using a mechanised device to simulate drops from a harvester (Hole et al.,1999) and piercing the surface of a carrot and recording whether or not a fracture propagates (Dickson, 1966).

Ideally, the technique employed to measure splitting susceptibility should be easy to use, permit a large number of measurements to be taken in short period of time in the field, and provide a measure of splitting susceptibility that is independent of carrot size. Dropping carrots from a set height, or a series of heights, onto a metal plate is the most commonly used method as it simulates the impacts carrots may receive during the harvesting and handling process. However, the results are strongly influenced by carrot size as heavier carrots receive a greater impact force than lighter carrots (e.g. Hole et al., 1999) and are therefore more likely to split. Earlier researchers involved in breeding used a technique that involved piercing the surface of a carrot with a knife and recording whether a fracture propagates or not. The knife technique, while easy to use, does not simulate impacts received during harvesting and is therefore considered to be of minimal value. Other techniques that involved taking roots back to the laboratory are questionable as moisture lost during the storage or transport may affect the outcomes.

In this study, splitting susceptibility of carrot taproots was assessed using a hand held penetrometer (Fruit Pressure Tester FT 327, EEFEGI, Italy), fitted with an angular tip with a blunt end (Figures 2 and 3). The design and the usage of the penetrometer was identical to that developed and reported by Gracie (2002). The widest part of the tip was aligned with the longitudinal axis of individual taproots and pressure was slowly applied to the surface as shown in Figure 2. A taproot was deemed to have split when a longitudinal fracture propagated a minimum distance of 15 mm. The load required to induce a taproot to split was recorded in pounds, the units on the penetrometer. For consistency the pressure was always applied approximately 3 cm below the crown at a rate of approximately 2 4 pd's per second. Only taproots that had no physical defects were used and all carrots were tested immediately after hand harvesting (Gracie, 2002).

Gracie (2002) observed a linear relationship between the load applied using the penetrometer and proportion of taproots splitting and from this developed a weighted index, referred to as splitting index (SI), to quantify the splitting susceptibility of a population of carrots. Furthermore, he was able to show that the splitting susceptibility was not linked to carrot diameter and length. Given the strong correlation between taproot weight with carrot diameter and length and it also provided a measure of splitting susceptibility independent of weight.

The spitting propensity of carrots in this study was presented as the percentage of taproots splitting with incremental increases in load (2 pounds), and as a weighted index (termed Splitting Index). The maximum load applied to carrots was 24 pounds.

A Splitting Index (SI) was calculated by dividing the range of load applied (0-24 pd) (10.9 kg), into six 4 pd (1.8 kg) increments. Carrots that split were weighted according to their ease of splitting as shown in the formulae.

$SI = (6a + 5b + 4c + 3c + 2e + 1f) / n$

Where n is the total number of carrots tested in each sample, and a,b,c,d,e,f are the number of carrots that propagate a split within the load range given by the groups A,B………F respectively.

Load required to induce splitting

Group	Pounds
A	0.0 – 4.0
B	4.1 – 8.0
C	8.1 – 12.0
D	12.1 – 16.0
E	16.1 - 20.0)
F	20.1 – 24.0
G	>24.0

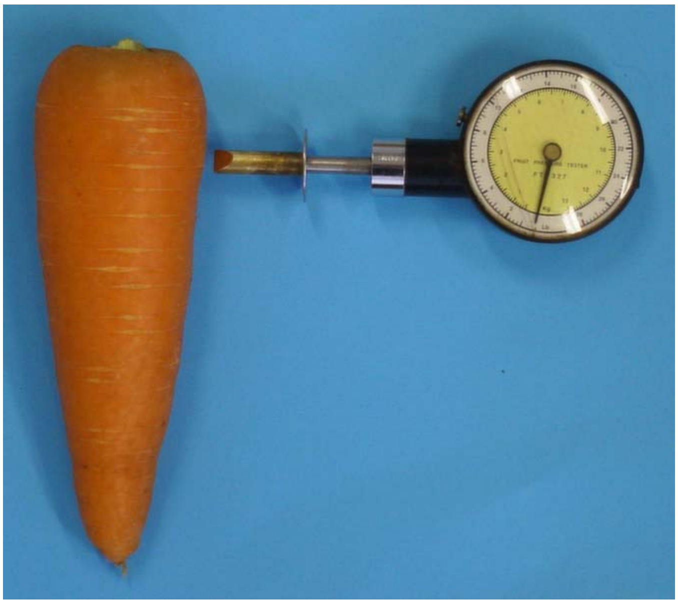


Figure 2. Hand held penetrometer with modified tip. Photo sourced from Gracie (2002) with permission.

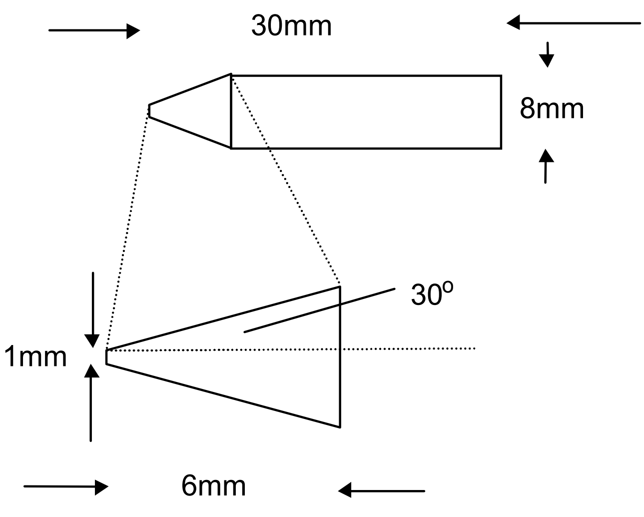


Figure 3. Dimensions of the modified tip. Diagram sourced from Gracie (2002) with permission.

A number of validation tests were conducted to demonstrate the relationship between dropping carrots from a set height, the most common technique used in carrot splitting research, and the load required to induce splitting using the modified hand held penetrometer. In an assessment undertaken at Forthside Vegetable Research Farm mature carrots were either dropped from a set height; 20, 40, 60 or 80cm onto a steel plate, or assessed using the modified penetrometer. All assessments were undertaken on carrots immediately after harvest and the carrots were randomly allocated to a treatment.

Figure 4 below shows the relationship between drop height and cumulative number of carrots splitting, while Figure 5 illustrates the relationship between the load required to induce splitting using the hand held penetrometer and percentage carrot splitting. The percentage carrots splitting when dropped from a height of 20cm corresponded to a load of 8 pounds using the hand held penetrometer in order to cause the same level of splitting. Similarly, dropping carrots from a height of 40 cm corresponded to a load of 9pds and when dropped from a height of 60cm, 11.5pds and 80 cm, 12pds.

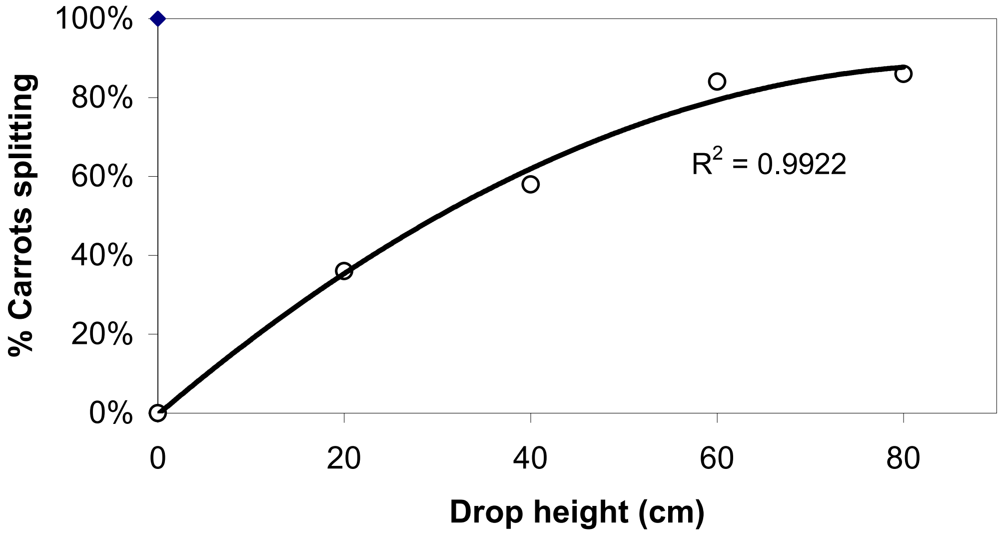


Figure 4. Relationship between drop height and percentage of carrots splitting

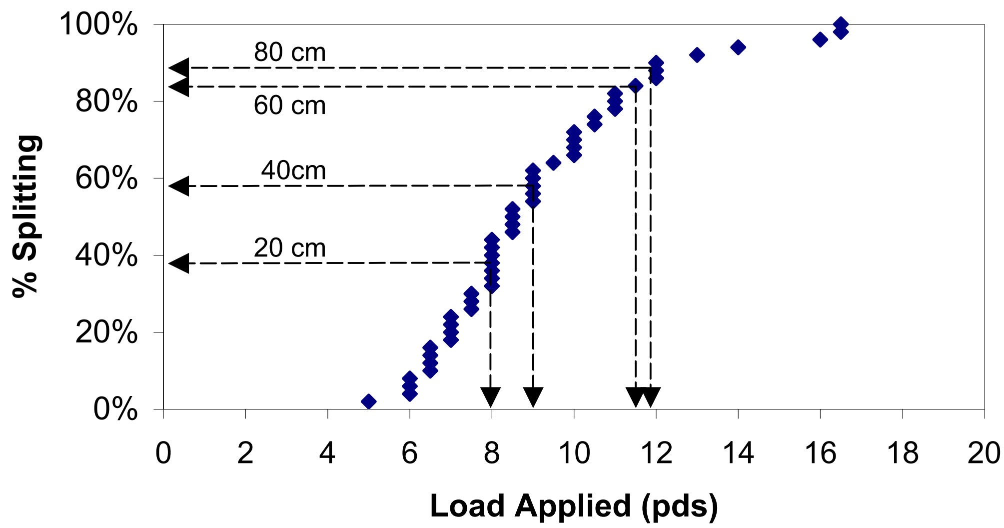


Figure 5. Percentage of carrots splitting with increasing load applied using the splitting penetrometer. The corresponding proportion of carrots splitting when dropped from a height of 20, 40, 60, or 80cm, and the load applied using the penetrometer is illustrated on the graph.

Splitting Susceptibility Assessment

The splitting susceptibility of carrots was recorded in this study as a weighted splitting index using the hand held penetrometer, as described above. In all the experiments conducted in this project carrots were assessed at dawn immediately after hand harvesting. Each splitting index value was obtained from 30 unblemished carrots, unless noted otherwise. The splitting index values commonly ranged from 1.0 to 3.0. The relative splitting susceptibility is described below.

Splitting Index	Splitting Susceptibility
>2.5	extreme
2.0 – 2.5	high
1.5 – 2.0	moderate
< 1.5	low

Time of cut and carrot splitting susceptibility

Partial defoliation of mature carrots the day prior to harvesting has been shown to significantly reduce carrot splitting susceptibility compared with untreated plots (Gracie, 2002). However, in all the partial defoliation trials conducted to date the trimming treatment was always applied between 1:00-2:00pm when leaf water potential was at its lowest and leaf starch levels were thought to be at their highest. Although this theory has not been validated (Gracie, 2002). Two separate trials were conducted to investigate if applying the foliage trimming treatments at other times of the day affected the carrot splitting response.

Being able to apply the defoliation treatments at other times of the day with the same reduction in splitting susceptibility response would provide greater flexibility in a commercial situation.

Methodology

Two trials were undertaken to examine whether the time of day the trimming treatment was applied had an effect on carrot splitting susceptibility. The trials were undertaken at separate locations in the 2001/2002 carrot growing season on the northwest coast of Tasmania, at Penguin and Abbotsham on the *23-24* January 2002 and 11-13 February 2002 respectively. Splitting susceptibility was measured the following day in the trial at Penguin, and two days later for the trial undertaken at Abbotsham. Splitting susceptibility was measured at dawn, when carrots are most susceptible, in both trials.

Foliage trimming treatments were applied at 5 different times; 8am, 10am, 12pm, 2pm and 4pm in the trial at Penguin. The same trial design was implemented at Abbotsham, with the exception that the first trimming treatment was applied at 9am instead of 8am. In both trials the trimming treatments applied were compared with untreated plots in a randomised complete block design. Both trials consisted of three blocks each divided into six plots. Each treatment was randomly allocated to a plot, a 1-metre length of a bed containing 6 rows of carrots, in each block. A 0.5 m buffer separated each plot. The trimming treatment consisted of vertical and horizontal cuts using a hedge trimming shears. Horizontal cuts were applied 30cm above soil level and vertical trimming was applied 15cm from the centre of each carrot row. The foliage trimming treatment chosen was reported to have the greatest effect in reducing splitting propensity (Gracie and Brown, 2003).

Results and Discussion

Data showing the effect of time of day at which foliage trimming treatments were applied are reported as a spitting Index (SI), and shown in Figures 6 and 7, for the trials conducted at Abbotsham and Penguin respectively.

The trial conducted at Penguin (Figure 7) was assessed the dawn following treatment applications and data were analysed as a two-way analysis of variance. No significant difference (P>0.05) was observed between the five separate foliage trimming application times and the untreated plots. However, there was a trend of increasing splitting susceptibility with later application time. Also, the untreated control plants had the highest splitting susceptibility.

The splitting susceptibility of carrots in the trial conducted at Abbotsham (Figure 6) was assessed at dawn 2 days after treatment application. No significant difference (P=0.09) was detected at the 95% confidence level between the different times of applying the leaf-trimming treatments, however, there was a significant difference at the 90% confidence limit between untreated plots and leaf trimming treatments applied at 9am and 10am. Similar to the trial conducted at Penguin, the data exhibited a trend towards higher splitting susceptibility with treatments applied later in the day. Furthermore, the highest splitting susceptibility level was again observed in the untreated control plots.

It is unclear whether the general increase in splitting susceptibility associated with later application times of leaf trimming was due to a greater delay between treatment applications or attributed to the physiological status of the plants at the time of treatment. In both trials untreated control carrots had the highest splitting susceptibility. A greater number of replicates may have revealed a significant difference between the leaf-trimmed plots and the untreated plots.

The larger difference between the untreated and treated plants in the trial conducted at Abbotsham may be a result of the higher splitting propensity of the crop cultivated at Abbotsham (untreated plants SI = 2.57, average of all treated plots SI = 1.96) than at Penguin (untreated plants SI = 2.28, average of all treated plots SI = 1.89). The soil at the first Penguin trial site was noticeably dry possibly reducing the overall susceptibility of the carrots to splitting in this trial. Low soil moisture leading to lower rates of photosynthesis and hence lower carbohydrate storage and growth overnight might explain why no difference is apparent between the control and trimmed carrots in this first trial. Although the first trial was irrigated the night following treatment application, this was done during the evening, and would not have ameliorated the effect low soil moisture status had on the plants photosynthetic activity the day the trimming treatments were applied.

From the two trials undertaken there is evidence that the time of day leaf trimming is applied does not have an effect on the carrots susceptibility to splitting. However, since the trimmed carrots splitting response did not differ statistically to the uncut controls, this conclusion is tentative.

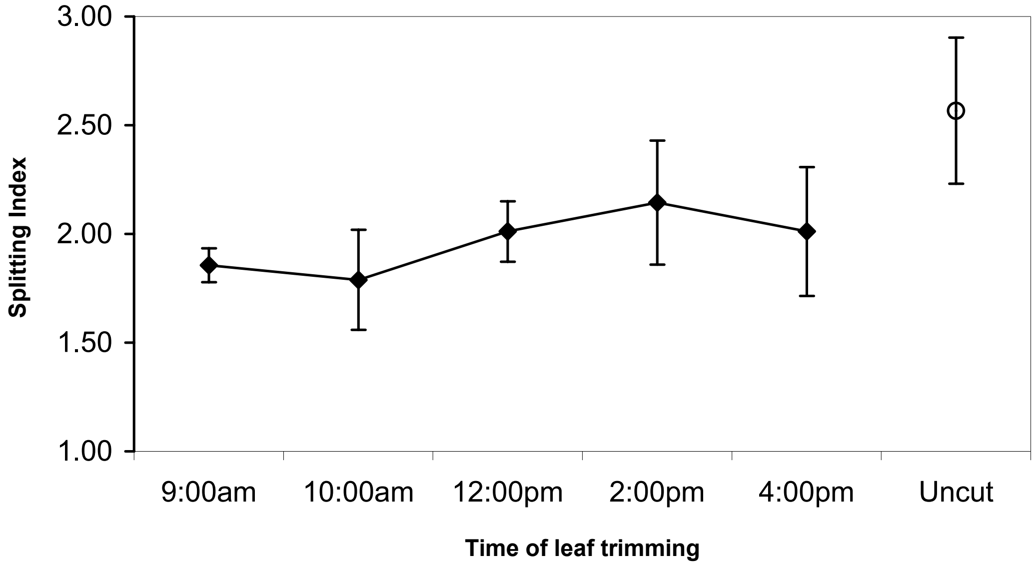


Figure 6. The effect of leaf trimming applied at different times of the day (diamond) on carrot splitting susceptibility. The leaf trimming treatments (vertical and horizontal cuts) were applied to a commercial Kuroda crop at Abbotsham on the 23-24 January 2002 and were compared with untreated control plants (open circle). Splitting susceptibility measurements were recorded at dawn 2 days after treatments application. Mean values ± S.E.M. shown, n = 3.

Sorensen and Harker (2000) proposed that the circumferential stress that develops in the carrot taproot leading to splitting is derived from the differential in tissue extensibility properties across the phloem tissue. The authors did not account for a possible gradient in turgor potential, the intra cellular hydrostatic pressure, between the two regions. Therefore in addition to recording splitting susceptibility taproot water status was also recorded at the Penguin site to determine whether the effect of leaf trimming in reducing splitting propensity recorded by Gracie and Brown (2003) was due to a change in the gradient in turgor potential between the inner and outer zone of the phloem tissue.

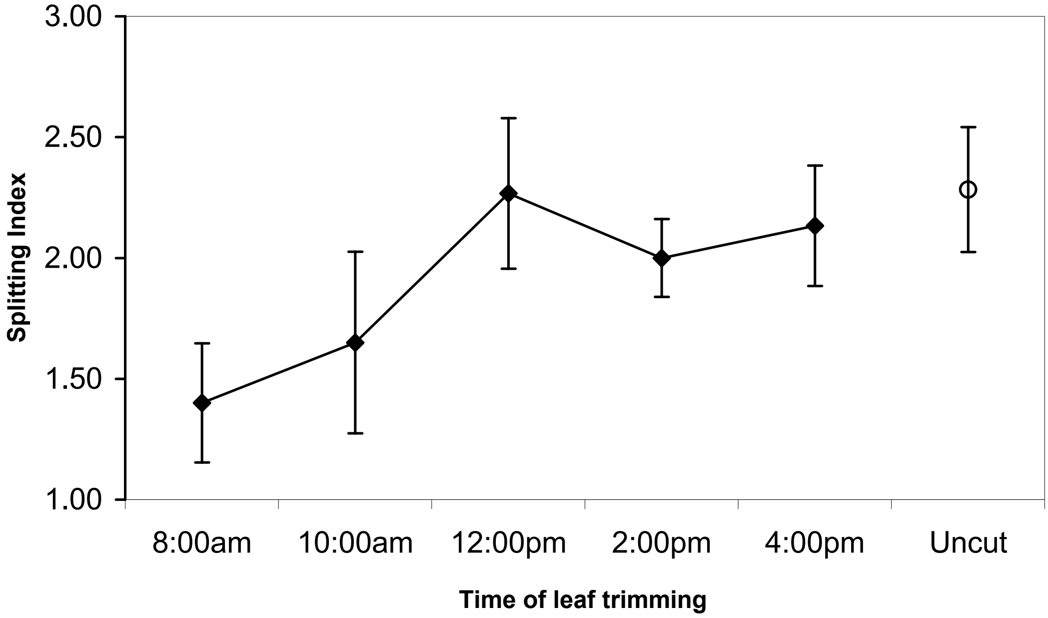


Figure 7. The effect of leaf trimming applied at different times of the day (diamond) on carrot splitting susceptibility. The leaf trimming treatments were applied to mature Kuroda carrots grown Penguin on the 11-13 February 2002 and were compared with untreated control plants (open circle). Splitting susceptibility measurements were recorded at dawn 2 days after treatments application. Mean values ± S.E.M. shown, n = 3.

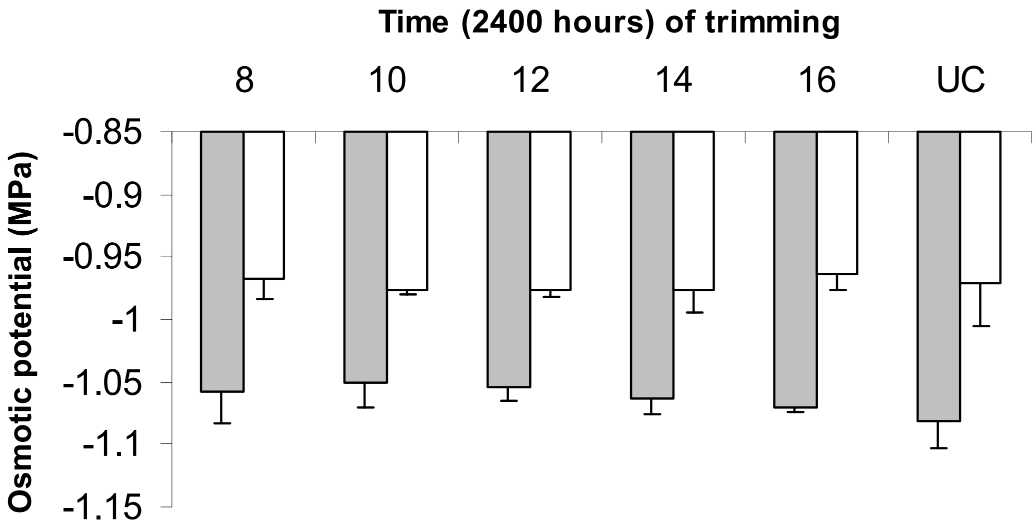


Figure 8. Osmotic potential of taproot phloem tissue at pre-dawn after trimming leaves at different times the previous day. Phloem tissue within 1mm of the vascular cambium (filled) and from the periderm to the within 1mm of the vascular cambium (open). Mean values ± SEM bars shown. UC = uncut control.

Given that all water status measurements were recorded pre-dawn in this study the entire carrot (leaf and taproot) can be assumed to be in equilibrium with the soil water potential. Thus leaf water potential was recorded as a measure of taproot water potential. This was achieved using a Scholander type pressure bomb on five carrots per treatment as described by Tyree and Hammel (1972). The pre-dawn leaf water potential was recorded to be –0.15MPa at the Penguin experimental site. This water potential value was consistent with the high soil moisture content noted since the trial site received irrigation during the night period prior to field pre-dawn measurements.

As mentioned earlier, the water potential of the entire carrot taproot is assumed to be in equilibrium with soil water potential pre-dawn, thus differences in osmotic potential between the tissue regions within the plant should mirror turgor potential since turgor potential is calculated as the difference between osmotic and water potential (i.e., turgor pressure = total water potential – osmotic potential). For concision only osmotic potential readings are given in this report.

Osmotic potential of the phloem parenchyma was recorded by taking a radial core of phloem. Excised tissue segments were immediately snap frozen in liquid nitrogen after sampling. The sap was later expressed and its osmotic potential measured using an osmometer. Full details of the method used to determine osmotic potential can be obtained from Gracie (2002).

Two segments of tissue were sampled from the phloem tissue core; inner phloem tissue within 1mm of the vascular cambium and from the periderm to within 1mm of the vascular cambium. The osmotic potential of the inner 1mm of phloem tissue was recorded separately as the short duration between trimming treatment and measuring osmotic potential is more likely to affect this inner phloem given that the axial flow of assimilates from leaves is largely through this region of the taproot. In addition to this, a small change in the internal pressures (eg turgor) in the inner phloem region can have a large effect on the tangential stress that ensues and consequently the splitting susceptibility of taproots.

Consistent with observations noted by Gracie (2002), the inner phloem tissue region had a significantly lower osmotic potential, and therefore higher turgor pressure, than the remainder of the phloem (Figure 8). No significant difference in osmotic potential between trimming times was recorded. Given that leaf trimming applications did not significantly affect carrot splitting propensity in this trial it is difficult to ascertain whether reductions in splitting propensity previously recorded were due to adjustments to the osmotic potential (and consequently turgor pressure) or a result of decreased radial 'tissue growth' (cell division and expansion) due to reduced assimilate supply to the newly synthesised cells.

Type of cut and splitting susceptibility.

Only a limited number of trials investigating the effect of leaf trimming on carrot splitting propensity had been undertaken prior to this project commencing. In all the preceding research foliage was trimmed vertically at 100mm from the centre of the carrot row, and horizontally at 300mm above the carrot crown (Gracie, 2002). The trimming treatments imposed were chosen as they removed the maximum amount of foliage whilst still permitting mechanical harvesting by top lifting. Further work is therefore required to examine the efficacy of the level of defoliation and the type of trimming applied on splitting propensity before construction of customised trimming implements. In this section the foliage trimming regimes and cutting treatments examined by Gracie (2002) are compared with alternative techniques.

Methodology

Four different trimming treatments were compared with untreated plots in a randomised complete block design consisting of 3 blocks. The trial was conducted in a commercial carrot crop at harvest maturity in Barrington. The four trimming treatments assessed were:

1. Vertical cuts 100 mm from the centre of double rows (Side 100)

2. Vertical cuts 200 mm from the centre of double rows (Side 200)

3. Vertical cuts 100 mm from the centre of double rows plus with horizontal cuts 300mm above soil level. (Top&Side)

4. Complete defoliation (Com Def)

Trimming treatments were applied between 8:00-9:00am the morning prior to the measurement of splitting susceptibility.

Results and Discussion

A two-way analysis of variance of the data revealed a significant block affect. However, no significant difference (P<0.05) in splitting propensity was recorded between the various foliage trimming regimes and the untreated control (Figure 9). The lack of treatment affect and the presence of a block effect provide preliminary evidence that there may be an interaction between some uncontrolled factors and leaf trimming. Unfortunately the treatments were not replicated within a block to determine if a treatment by block interaction existed.

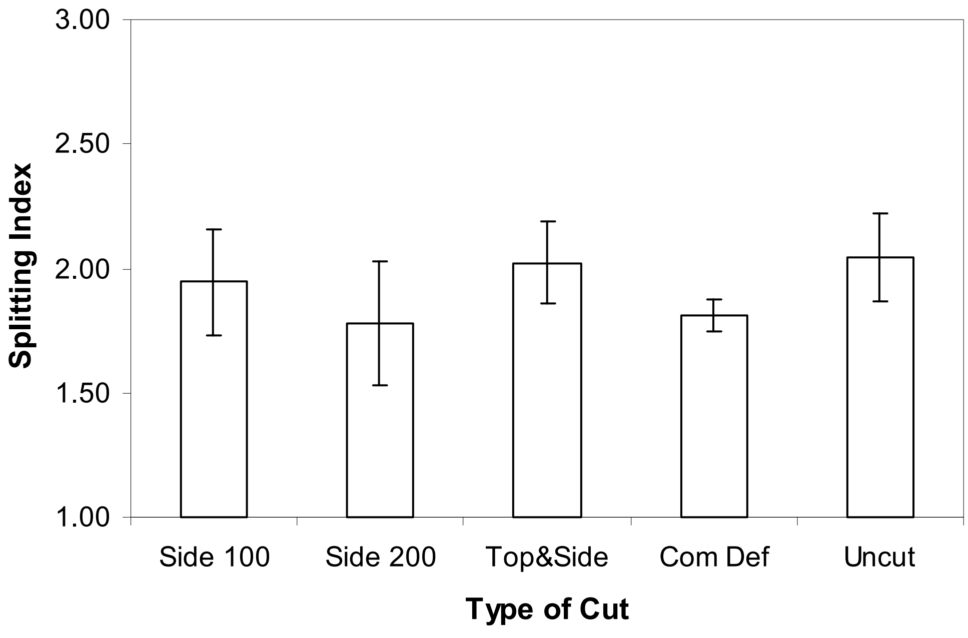


Figure 9. Splitting susceptibility response to the four leaf-trimming regimes and untreated control. Trimming abbreviations are given in the above methodology section. Mean values ± S.E.M. are shown.

The lack of response to leaf trimming observed across all treatments (Figure 9) could arise in a situation where carrot growth has slowed substantially due to low soil water levels, or cold overcast conditions. Under such circumstances assimilate movement from the leaf tissue to root storage cells would be greatly reduced and thus splitting susceptibility could possibly be similar for any carrot regardless of how much leaf material was removed. These conditions may partially account for the results obtained.

Type of cut and the duration of the treatment effect

Innovative strategies require a degree of flexibility for them to be adopted and implemented within vegetable production programmes since variables such as inclement weather, machinery breakdown or other unforeseeable events that contribute to alterations to planned schedules. If trimming treatments are to be applied in a commercial context, knowing the effect of a delayed harvest after leaf trimming is essential. Initial data reported by Gracie and Brown (2003) indicated that the partial defoliation treatment declined in effectiveness in reducing splitting with increasing time elapsed from application, and may even increase splitting propensity if left for more than 2 weeks. However, the data reported by Gracie and Brown (2003) was based on correlative analysis from a number of different crops and locations. This study investigates the interaction between trimming strategy and duration of storage prior to harvesting within a crop.

Methodology

Two trials were conducted at Forthside Vegetable Research Station (FVRS) to investigate the interaction between leaf trimming strategy and the duration it suppressed carrot splitting susceptibility. Both experiments were implemented as split plot designs with the main plots consisting of 3 blocks to which treatments were randomly allocated in a randomised complete block design. Sub plots were time of harvest following treatment application. In the first trial a vertical leaf trimming treatment was compared with untreated control carrots. The vertical trimming treatments, orientated parallel with the planted rows, was made 200mm to both sides from the centre of double rows. Trimming was undertaken between 8am and 9am.

In the second trial at Forthside Vegetable Research Station (FVRS) partial and complete defoliation treatments were compared with untreated control plots. The partial defoliation treatment involved both vertical and horizontal trimming of the plants. Vertical trimming was applied 100mm from the centre of double rows and horizontal trimming 300mm above the soil surface. In both trials the treatments assessments of carrots splitting were recorded 1, 5, 8, 10 and 12 days after application.

Results and Discussion

In the first trial, the side cut of 200mm from the centre of the double rows was used to emulate the then current setting of a prototype leaf-cutting implement. Although the trimming treatments had a lower splitting index than the untreated plots 1 day after treatment, the effect was not significantly different ($P<0.05$). No significant difference in splitting susceptibility was recorded between the trimming treatment and untreated control plots on any of the harvest days (Figure 10). Splitting susceptibility was generally low in this trial due to low soil moisture levels placing the carrots under moisture stress. Furthermore, the canopy of the plants in this trial was relatively short; therefore the vertical trimming treatment removed very little foliage. The combination of these factors may have contributed to the lack of treatment effect exhibited in the first trial.

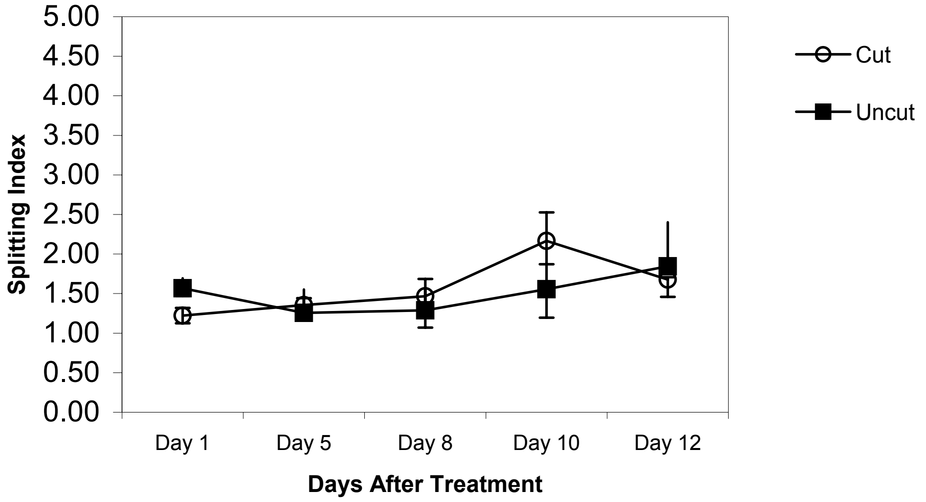


Figure 10. Trial 1. Splitting susceptibility of carrots with time after trimming foliage vertically 200 from the centre of the double rows (Cut) or left untreated (Uncut). Mean values shown, n = 3, SEM bars where greater than the symbol.

In the second trial, a significant ($P<0.05$) reduction in splitting susceptibility associated with defoliation and an interaction between treatment and time of harvest was recorded. At all five harvest dates the untreated control plots had the highest level of splitting susceptibility (Figure 11). Complete defoliation resulted in the greatest reduction in splitting susceptibility. From day 5 until day 12 the plants that were completely defoliated had an extremely low splitting susceptibility and this level of splitting (SI = 0.7) remained relatively constant over that duration. Significant rainfall was received on day 5.

While the splitting was approximately the same one day after application for all treated and untreated carrots, the partial defoliation and untreated plots tended to fluctuate more in splitting susceptibility from day 5 to 12 than the completely defoliated plots (Figure 11). The partially defoliated plants had a significantly lower splitting propensity than untreated controls on day 8, when splitting susceptibility of control plots was at its highest. However, the effect of partial defoliation on reducing splitting susceptibility disappeared by day 12 and was found similar to the level recorded for untreated plants.

Overall, splitting susceptibility of untreated plants was higher than partial defoliated and complete defoliated plants at every harvest date and the greatest reduction in splitting susceptibility was associated with complete defoliation. The rainfall received on day 5 may explain the increase in splitting susceptibility seen on day 8. The reduction in splitting susceptibility following complete defoliation lasted for a the 12 day period, while partial defoliation reduced splitting susceptibility relative to untreated plots for a 10 day period. This latter outcome concurs with data reported by Gracie (2002) that indicated that the benefits of partial defoliation only persisted for a 10 day period.

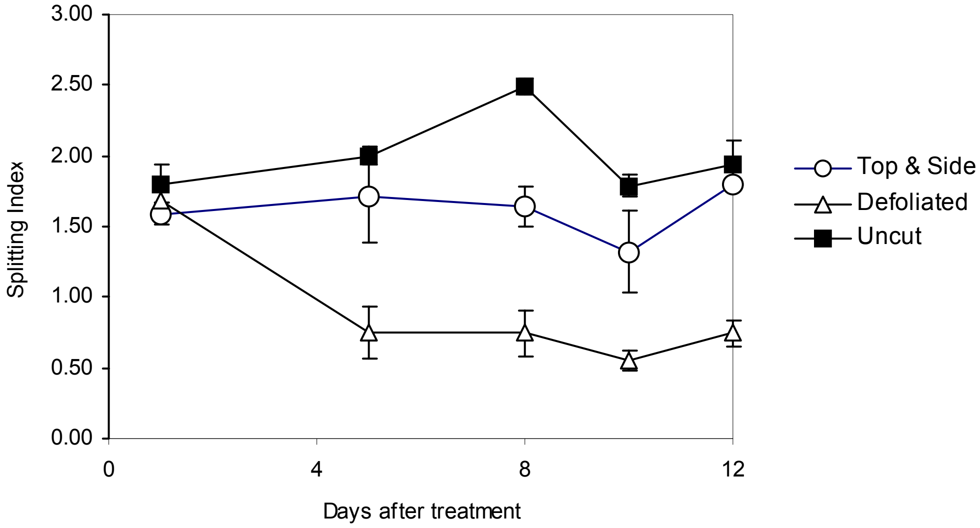


Figure 11. Trial 2. Splitting susceptibility of carrots with time after trimming foliage both vertically and horizontally (Top and Side) complete defoliation (Defoliated) or left untreated (Uncut). Mean values shown, n = 3, SEM bars are shown where greater than the symbol.

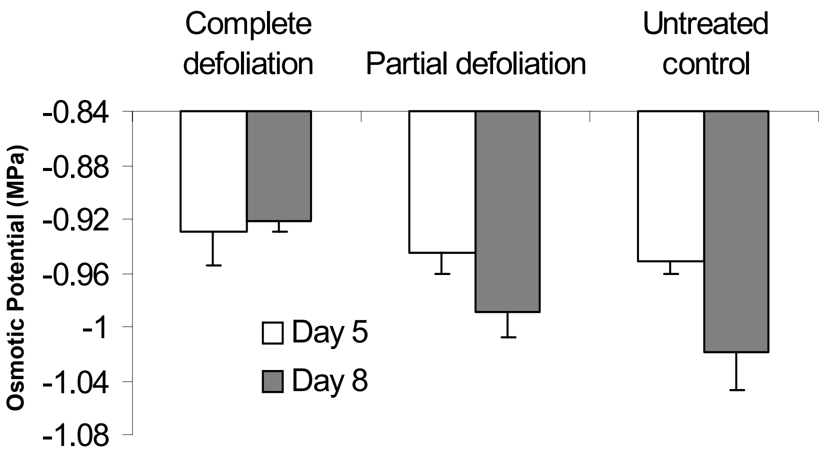


Figure 12. Osmotic potential of taproot phloem tissue 5 and 8 days after either; complete defoliation, vertical and horizontal trimming (partial defoliation) or no defoliation (untreated) of carrots plants. Measurements were taken at pre-dawn. Mean values ± SEM bars shown

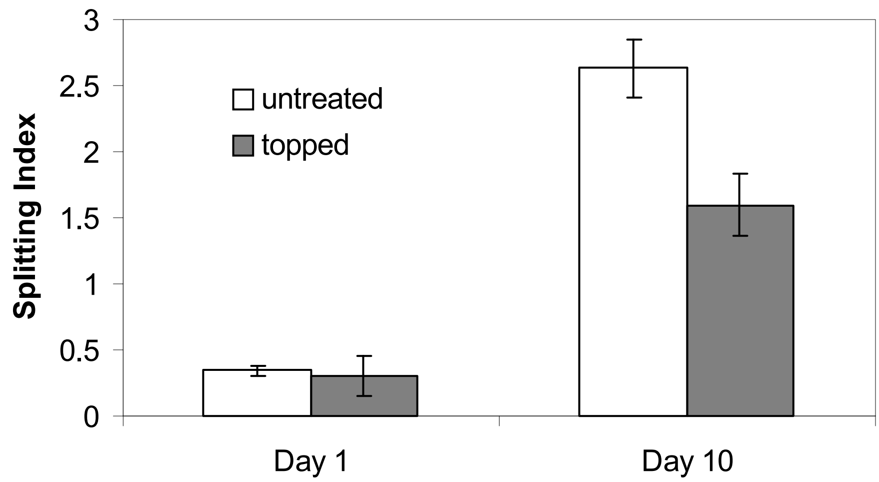


Figure 13. The effect of trimming carrot leaves horizontally (topped) 300 mm above the crown of the taproots on splitting susceptibility 1 and 10 days after treatment. The treatment was applied to a commercial crop at harvest maturity grown at Penguin. Mean values ± S.E.M. shown, n=4.

For trial 2 (Figure 11), measurements of taproot water status were also recorded on day 5 and 8. These measurements were taken to further examine the underlying role of phloem turgor pressure in inducing splitting in untreated and defoliated plants. The results are shown in Figure 12. The method used to determine total water potential and osmotic potentia of the tissue was the same as that outlined in the section on the timing of foliage trimming. Given that the inner zone of the phloem parenchyma provides the impetus for splitting only the osmotic potential of the 1mm adjacent to the vascular cambium is presented (Figure 12). While no significant differences in splitting susceptibility were obtained 5 days after treatment application, differences at the 95% confidence limit were recorded on day 8. These results imply that the difference in splitting on day 5 was not due to differences in turgor in the inner phloem tissue zone and therefore was most likely associated with tissue growth. Conversely, 8 days after trimming the differences in osmotic potential recorded suggests that turgor of the inner zone may be contributing to the effect at the later harvest date. This increase in turgor is most likely associated with the rainfall received on day 5 of the trial. Therefore both the turgor in the inner phloem zone and the growth of the tissue may be playing a role in splitting depending on the circumstances.

Two commercial scale top trimming trials, without replication, were reported by Gracie (2002) to decrease the incidence of split carrots following mechanical harvesting. Thus, in addition to the trials mentioned above, further assessments of the effect of horizontal trimming on carrot splitting susceptibility were undertaken. Two trials were established in commercial crops at the time of carrot maturity. The crops were located at Penguin and Sassafras and the treatments were imposed on the on 4th February 2003 and 12th February 2003 respectively.

The Penguin crop had an extremely low splitting susceptibility level at the commencement of the trial (Figure 13) and under normal circumstance would not require preventative treatment. However, measurements taken 10 days after treatment revealed a significant increase in carrot splitting susceptibility in both the control and trimmed plots, with the trimmed plants increasing more than controls (though not significantly (P>0.05)) over that period. The increase in splitting susceptibility from day 1 to day 10 was most likely due to the influence of environmental variables, such as precipitation, temperature and irradiance.

The splitting susceptibility of carrots in the second horizontal trimming trial, located at Sassafras, was only recorded one day after treatment. No significant differences in the splitting index between the treated and untreated plants were identified (Figure 14). As this crop had a small canopy, it is thought that the small amount of leaf material removed was not enough to inhibit the production and movement of photosynthetic assimilate thus rendering the treatment ineffective.

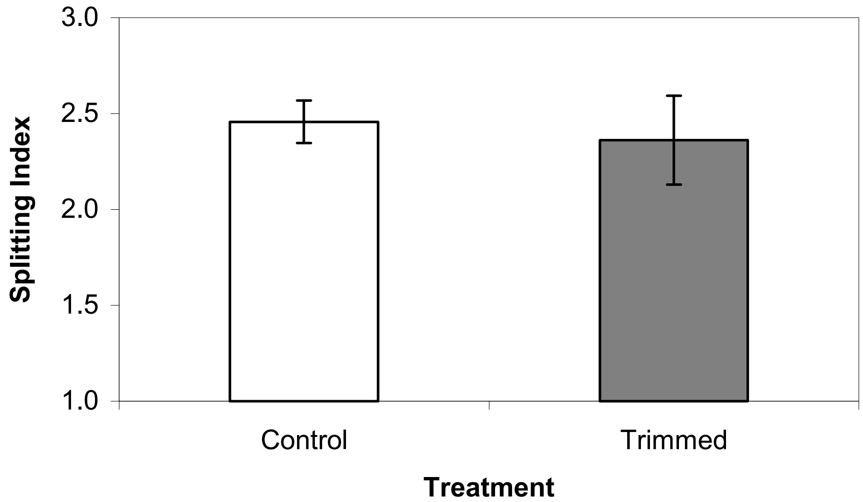


Figure 14. The effect of trimming carrot leaves horizontally (Trimmed) 300 mm above the crown of the taproots on splitting susceptibility 1 day after treatment. The treatment was applied to a mature crop grown at Sassafras. Mean values ± S.E.M. shown, n=4.

In summary the responses observed in this section of work indicates that where conditions are favourable for splitting, the response of the carrots to leaf trimming will last for up to twelve days. This response is influenced by both the environmental conditions encountered after trimming has been applied and by the relative proportion of leaf material removed. In general, the more leaf material removed, the greater the reduction in splitting susceptibility.

Soil moisture and carrot splitting susceptibility.

The unpredictability of carrot splitting susceptibility in response to leaf defoliation in the previous experiments may be associated with variation in the physiological stage of development of the carrot plant at the time of treatment and/or an interaction with uncontrolled variables such as environmental conditions. The large variance in splitting susceptibility from day to day within a crop indicates that environmental conditions are impacting on carrot splitting propensity. This anecdotal evidence concurs with recent findings that environmental conditions, such as soil water status, irradiance level and vapour pressure deficit all have a significant impact on the diurnal growth pattern of the carrot (Gracie, 2002).

Of all the main environmental variables such as air temperature, photosynthetically active radiation (PAR), humidity and soil moisture, only soil water availability is controlled to some extent in field agriculture. Given the links between irrigation regimes and incidence of splitting in fruit crops such as grapes (Lang and During, 1990) and cherries (Sekse and Tstass, 1998) fluctuations in soil water availability are also likely to be having a major impact on carrot splitting propensity. Gracie (2002) was able to show that a period of drought followed by irrigation results in rapid radial expansion of the mature carrot root. Undoubtedly this rapid radial expansion must result in increased circumferential stress and in turn increased splitting propensity. The work by Gracie (2002) was conducted on carrots grown in pots under controlled environmental conditions. This section examines the effect a fluctuation in soil water availability has on radial grown of the carrot taproot and inturn the carrot growth splitting. Other environmental variables such as temperature and humidity are also considered.

Methodology

An initial test was undertaken to assess whether irrigation was influencing a carrots tendency to split, by sampling a section of a crop that had been irrigated the previous night with an adjacent non-irrigated section of the same crop. The splitting susceptibility of carrot samples from both sections of the crop was assessed between 7:30-8:00am using the hand held penetrometer. The results shown below in Figure 15 indicate that increased soil water content enhances carrot splitting propensity.

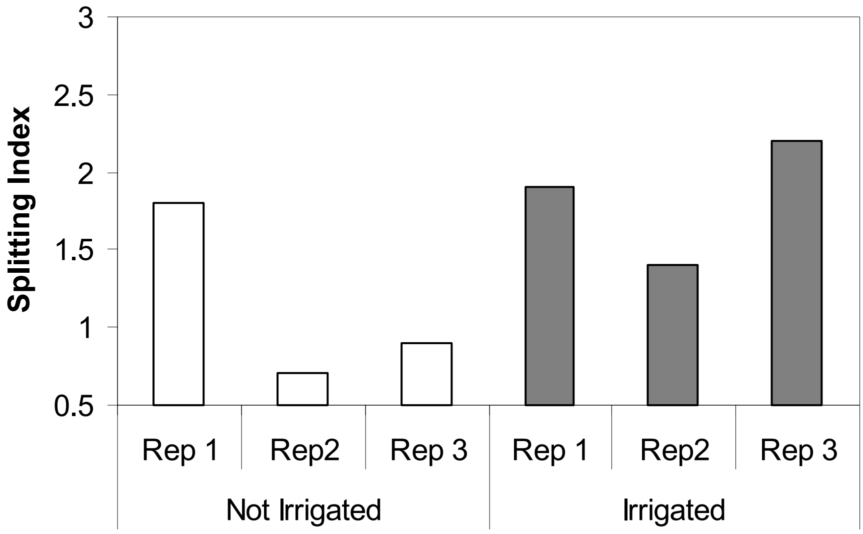


Figure 15. Splitting susceptibility of carrots from a section of a crop that received irrigation and a section that did not receive irrigation the night prior. Three replicates of 30 carrots were randomly selected from each section for assessment. Splitting susceptibility was recorded between 7:30am and 8am.

Further field trials were undertaken to extend this initial observation that increased soil water levels exacerbated splitting. Two detailed monitoring trials were undertaken in growing season 2002/03 to examine possible links between changes in splitting susceptibility and environmental conditions, in particular soil water availability. In both trials Watchdog data loggers (WatchDog 450^{TM}, Spectrum Technologies, Illinios) were positioned at trial sites and soil water availability was regularly recorded using a capacitance water measurement probe (Micro-Gopher®, Dataflow Systems Pty Ltd, New Zealand). Carrots samples were harvested at regular intervals to record changes in incidence of growth splitting and taproot growth parameters; diameter, length and weight. In addition to this, custom built electronic equipment was attached to the taproot to monitor diurnal growth patterns.

The first trial was carried out in a commercial crop at Cuprona between 25 March and 28 April 2003. Within the crop two sites were selected contrasting in aspect and level of wetness. The two sites were termed ‘dry’ and ‘wet’ to describe their relative profile. The site termed wet was in a gully, while the dry site was positioned on the rise that appeared to be relatively dry and difficult to irrigate due to the prevailing wind direction.

The second trial was undertaken at Forthside Vegetable Research Station (FVRS) from 16 May 2003 to 2 July 2003. Rainout shelters were constructed and used to create a dry site, which was compared with plots receiving ambient level of precipitation, plus irrigation when required.

Three $1m^2$ quadrat of carrots were harvested from each treatment at regular intervals and carrot fresh weight, diameter, length and incidence of growth splitting was recorded.

Results and Discussion

Carrots harvested from the wetter part of the crop, referred to as the wet site, had a greater weight, length and diameter than carrots harvested from the drier region (dry site) at each of the sample dates. The net increase in taproot fresh weight over the monitoring period (25 March 2003 to 28 April 2003) was approximately the same for the two sites, 80.9 grams and 77.0 grams for the wet dry site respectively (Figure 16a). Given that the growth rates over the sampling period were approximately the same for the two sites the higher mean weight of taproots harvested from the damp site must be due to a higher growth rate during the earlier stages of crop development.

The wet site (39.3 grams) had a mean weight nearly double that of the dry site (20.3 grams) at the commencement of the trial (Figure 16a). This difference in carrot growth and development at the start of the monitoring period supports the choice of sites for close monitoring.

A general increase in the incidence of growth splitting was observed at both sites (dry and wet) over the monitoring period, however the size of the increase was slight and only affected ca. 3.3% of the carrots by the end of the monitoring period (Figure 16d). On the first sampling date no split carrots were recorded in the wet site, while approx 0.5 - 1% of carrots were split in the dry site. The proportion of split carrots in the wet site tended to increase more rapidly over the following sampling days, while the dry site tended to increase at a lower rate. The increase in incidence of splitting at the wet site of 0.5% to 3.1% from the 11 April to 19 April corresponds to a period of high rainfall when the precipitation exceeded 90mm (Appendix 1).

Change in carrot diameter can be used to postulate changes in circumferential stress experienced by the taproot. Intuitively, rapid radial expansion of the taproot must surely result in increased circumferential stress and in turn increased splitting propensity, while a reduction in taproot diameter must result in reduced circumferential stress if all other variables such as temperature remain constant. An example of the diurnal change in carrot taproot diameter is shown in Figure 17. As evidence that monitoring diurnal changes of the taproot correlates with splitting propensity, a reduction in diameter of the carrot taproot during the daylight period coincides with a reduction in splitting propensity (Gracie and Brown 2000). The technique used to monitor changes in carrot diameter is illustrated in Appendix 2.

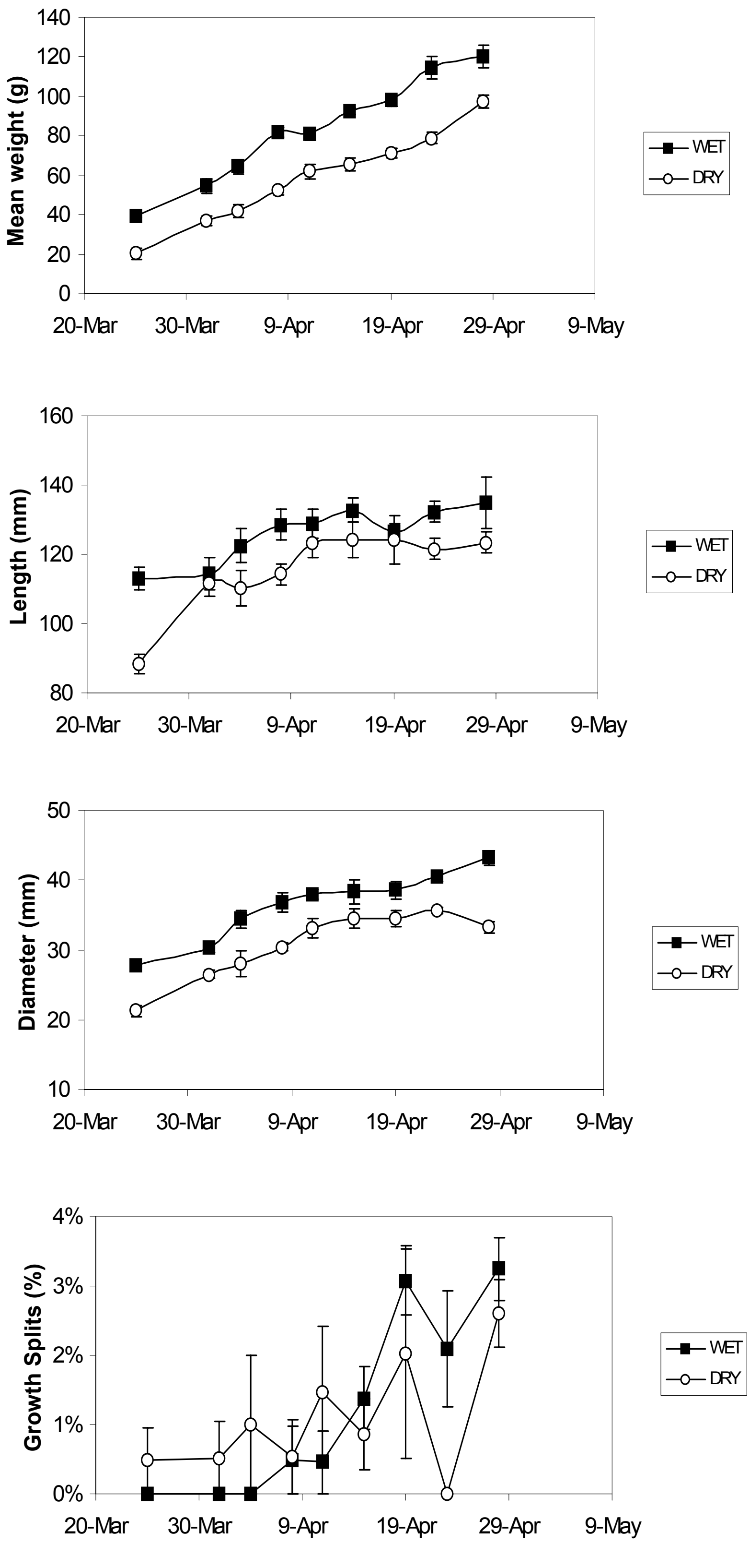


Figure 16. Change in taproot (a) mean weight, (b) length, and (c) diameter, and the corresponding change in (d) incidence of growth splitting. Data shown for a wet and dry site within a commercial crop at Cuprona. Mean values shown ± SE where greater than the symbol.

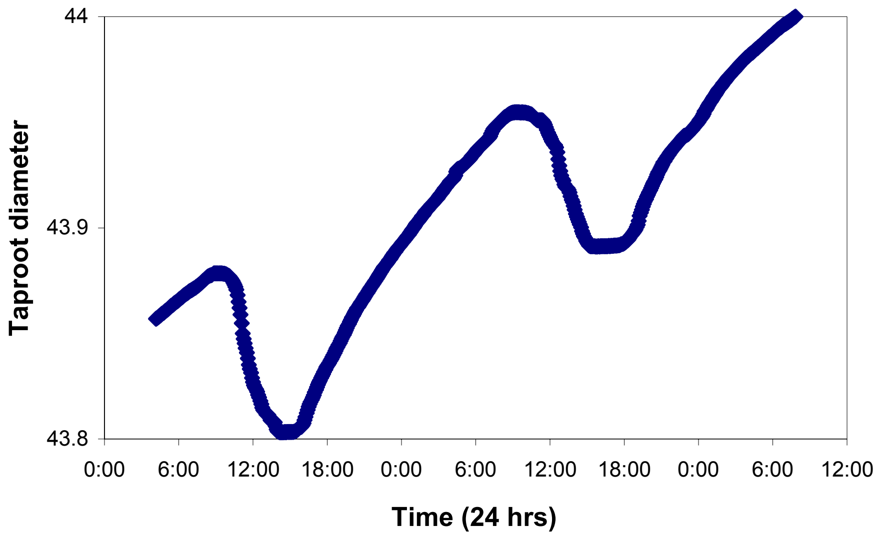


Figure 17. Change in carrot taproot diameter over a 48-hour period.

The second 'environmental x splitting' trial was located at Forth Vegetable Research Station. Instead of selecting two sites within this crop differing in soil moisture levels, rainout shelters (3m x1.8m) were used to eliminate precipitation from an area of carrots. The growth and development of carrots receiving precipitation, rain and irrigation, over the duration were compared with carrots receiving commercial levels. The length, diameter, fresh weight of taproots and the incidence of splitting in the irrigated site were monitored. Mean taproot fresh weight and incidence of growth splitting is shown in Figure 18. Carrots from the non-irrigated site were only sampled at the last harvest date, 2 July, due to the low number of plants that fitted under the shelter. Furthermore, sampling was restricted to those plants at the centre of the custom built shelters since any lateral movement of soil moisture may influence carrots at the periphery. The level of growth splitting did not significantly ($P>0.05$) increase over the duration of the trial with values ranging from 0.7% to 4.50%. Due to the large variation in incidence of splitting no significant difference was detected between the irrigated and non-irrigated part of the crop. No significant difference in growth rate between carrots under the shelter and those grown under ambient conditions was recorded, since the mean weight of carrots from the two treatments at the final harvest were approximately the same. Given that the May and June are wet and cold months in Tasmania, these conditions may have reduced growth rates and had an overriding effect on the trial outcomes.

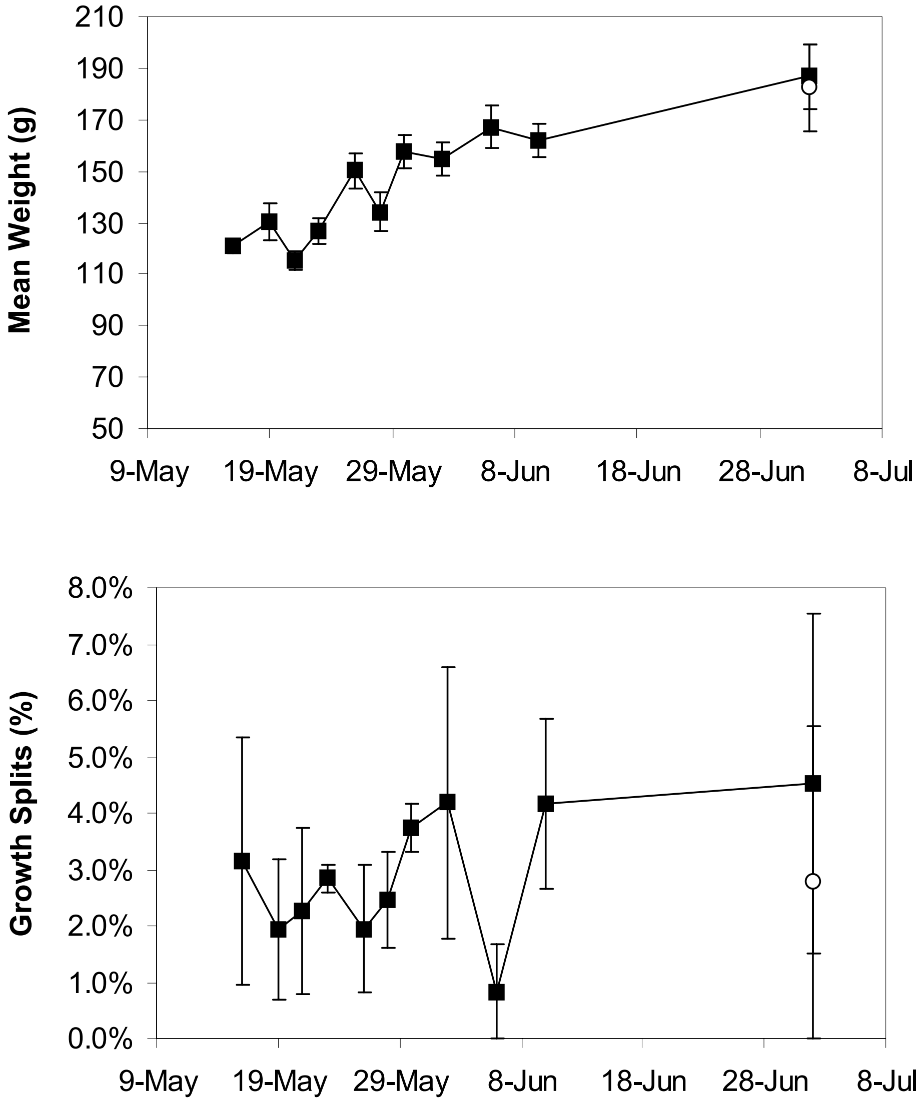


Figure 18. Change in (a) taproot mean weight, and (b) incidence of growth splitting. Data shown for a wet (■) and on the last sampling date, 2 July 2003, for a dry site (o) within a trial at FVRS. Mean values shown ± SE.

Commercial Implementation of the leaf trimming techniques

Leaf trimming as a method for reducing carrot splitting susceptibility has shown potential in small scale trials. As an extension of this work custom designed leaf trimming equipment was constructed and tested in commercial crops. Preliminary trials assessed vertical trimming and later trials considered both vertical and horizontal trimming. In addition to this a novel approach of complete defoliation and shear lifting was also examined.

Development of a vertical leaf trimming machine

A vertical leaf-trimming machine was constructed to fulfil two main functions: to prevent splitting and to alleviate the entanglement of leaves between adjacent rows. Carrot leaves are large and adjacent rows readily become intertwined making harvesting by top pulling inefficient, as the tangled leaves tend to create blockages in the cones.

The vertical cutting machine constructed consisted of 4-6 vertical hydraulically driven blade sets, set 100mm from row centres (Figure 19a). Blade sets were mounted on lawn mower blade bases. Blade bases were keyed into the drive shaft. Pipe with an inside diameter larger than the shaft was mounted between blade bases to prevent carrot leaves from wrapping around the shaft. The number of blade sets used depended on the row configuration being used on the beds. Outer blades were larger in diameter to cut leaves leaning over the edge of the beds. Blade rotation speed was set manually by adjusting hydraulic pressure supplied by the tractor to suit the prevailing conditions. Initially the machine was mounted to the front of the tractor, but in later trials it was mounted to the back. Mounting at the rear of the tractor provided greater control over lateral movement. When mounted at the front a slight change in the direction of the front tractor wheels resulted in large lateral movements of the cutter. This lateral movement was much less when the vertical trimmer was mounted at the rear. The vertical trimmer with control float wheel and micro-switches, to control height of the machine above the soil surface, is shown in Figure 19a-d.

A number of problems were initially encountered when using the vertical trimming machine. Firstly, lateral movement of the cutter resulted in the blades creating excess damage to the leaf petioles, leaving insufficient material for top pull harvesting. Secondly, control of the vertical height of the machine was critical to ensure adequate leaves were cut, yet avoided the undesirable effect of rotating blades contacting the soil and dangerously propelling stones and dirt. Hanging canvas curtain from the steel shroud minimised this latter problem. This issue was also addressed by ensuring blade rotation threw material away from the tractor. Thirdly, the preliminary trials revealed (data not presented for succinctness) that vertical trimming alone did not remove sufficient foliage to reduce splitting propensity, the primary reason for this machines construction.

Figure 19. (a) Early trimmer blade configuration; (b) Trimmed carrot canopy on left, untrimmed on right; (c) Hydraulic directional control switch operated by (d) Float wheel with micro-switch.

Leaf removal using a horizontal knife action

The outcomes from earlier experiments in this project indicated that the higher the proportion of leaf material removed the greater the reduction in splitting propensity. This was consistent with findings reported by Gracie (2002) that vertical trimming combined with horizontal trimming decreased taproot splitting propensity more than vertical trimming alone. Minor adjustments to the mechanised vertical leaf trimmer eliminated many of the initial problems, such as carrot damage associated with later movement. However, the device did not sever sufficient leaf material to reduce splitting propensity.

In further tests the effect of horizontal trimming was examined and was found to have negligible effect in reducing splitting. The combination of vertical and horizontal trimming was then assessed. Horizontal trimming was achieved using an onion leaf topper (*Make and model unknown*) and vertical trimming was undertaken using the custom designed vertical trimmer detailed above. With this configuration the vertical trimmer was mounted at the front of the tractor with the onion leaf topper trailing behind. Waste material from the onion leaf topper was expelled through a chute to one side of the machine. Mounting of the vertical trimmer at the front of the tractor prevented the tractor tyres from pulling foliage off plants in the outside rows of adjacent beds.

Methodology

The efficacy of the mechanised horizontal, and horizontal and vertical leaf trimming in reducing carrot splitting were assessed in 4 commercial crops in the growing season 2002/03. The crops were located at Cuprona, Kindred, Forth and Penguin. In each crop the trimming treatment was applied in a randomised complete block design and consisted of the two leaf trimming treatments regimes, and untreated control. Four blocks were used as replicates. Splitting susceptibility, using the modified hand held penetrometer, was measured at sunrise the day after treatment application.

After imposing the leaf trimming treatment the amount of leaf foliage remaining was quantified in two of the trials at Cuprona and Kindred. The leaves were severed from 5 randomly selected plants in each plot and divided into leaflets and petioles as shown in Figure 20 and the dry weight and cross-sectional surface area was then determined. The petiole material from the mature and immature leaves was combined

Results and Discussion

By weight, approximately 50% of carrot foliage is composed of leaflets (Figure 21), however, when measured as area, leaflets represented over 90% of the tissue (Figure 21b). The purpose of leaf trimming is to remove as much photosynthesizing leaf area as possible in order to reduce taproot growth rate and therefore carrot splitting, while leaving sturdy petiole material for mechanical harvesting by top pulling.

The horizontal trimming treatment removed approximately 36% of the leaflet material and when followed by vertical trimming removed an additional 32% (Figure 21). Very little petiole material was removed following either vertical or horizontal trimming. In later commercial trials it was found that the amount of material removed by the trimmer or trimmer- leaf topper combination could potentially interfere with the top pull harvester. To avoid this it would be required for foliage waste to be directed away from the carrot canopy.

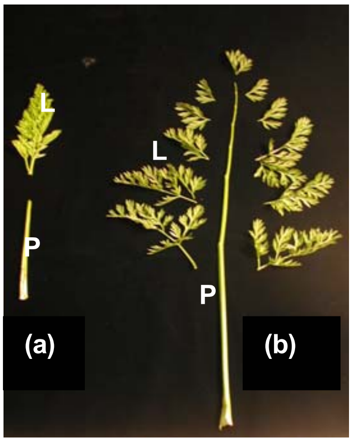


Figure 20. Carrot leaves were separated into (a) immature and (b) mature leaves then subdivided into leaflets (L) and petioles (P) as illustrated above.

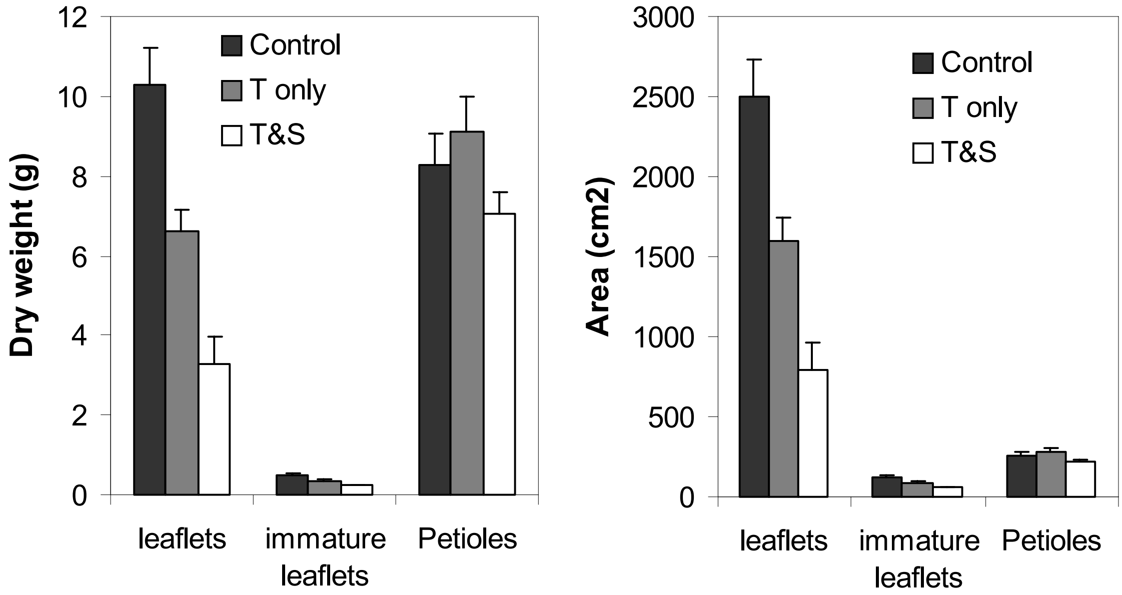


Figure 21. (a) dry weight and (b) cross sectional area of petioles and leaflets after horizontal trimming (T only), vertical and horizontal trimming (T&S), or leaving plants untreated (Control). Bars represent SEM. Crop planted at Kindred.

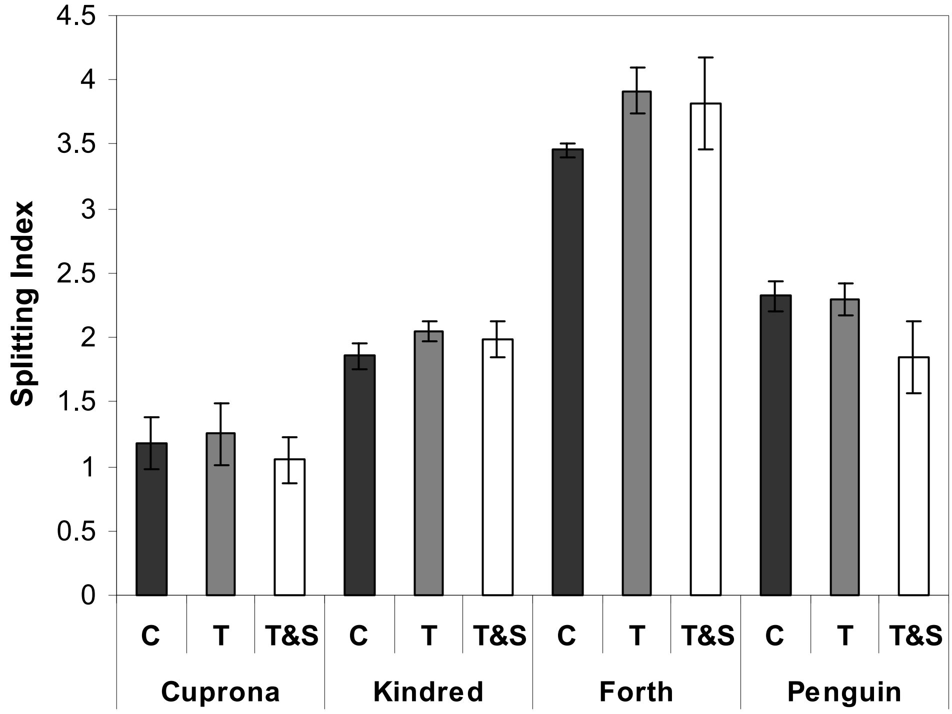


Figure 22. Splitting Index of untreated control plants (c), plants receiving horizontal trimming (T) and Horizontal and vertical trimming (T&S). average shown n=3 or 4. Bars represent SEM.

Splitting Indices recorded in the four separate leaf trimming trials are shown in Figure 22. The four commercial chosen crops represented a large range in splitting susceptibility, however no significant differences ($P>0.05$) were recorded between trimming treatments and the untreated control in any of the crops. The reason for the absence of any effect from leaf trimming on splitting propensity in these trials is unclear.

Complete leaf removal and harvest by shear lifter

In an earlier study complete foliage removal was found to reduce splitting propensity over a 12-day period. The reduction in splitting combined with halting carrot growth enables this treatment to used strategically in crops that have reached the required size range, but are not able to be harvested due to delays in the harvesting program. Complete defoliation treatments would require a change in the harvesting technique since the conventional harvesting mode is by top pulling, which requires about 30cm of sturdy leaf material. Therefore the practicality of complete defoliation combined with an alterative harvesting technique, shear lifting, similar to that used to harvest processing carrots and potatoes, as an alternative option to current harvesting technologies is examined.

Methodology

Three trials were conducted to compare the quality of carrots after harvesting by top pulling and shear lifting. One trail was undertaken at the Forthside Vegetable Research Station (FVRS) and two trials were undertaken in commercial crops (cv. Kuroda) at Sassafras. Only two of the trials were analysed in this report, one from Sassasfras and the other from FVRS. Carrots that were harvested by shear lifting had been completely defoliated just prior to harvesting, while carrots harvested by top pulling were left untreated (were not defoliated). Carrots were sampled at specific points in the harvesting process and an experienced carrot quality assessor evaluated the carrot samples for physical damage.

Damaged carrots fell within the following categories.

Scruffy top: amount of foliage attached to the taproot exceeds market requirements

Splits: longitudinal fractures (<5mm wide) that occur during harvesting operations

Cracks: longitudinal fractures (>5mm wide) that occur may have occurred during the growth of the crop or at harvest. Most cracks of this type have occurred during crop growth.

Broken: carrots that break radially

Side damage: physical damage to the side of the taproot

Shoulder damage: physical damage to the shoulder of the taproot

Results and Discussion

The proportion of carrots that were physically damaged at critical points in the two harvesters (shear, shear web, roller and bin) was compared. The shear lift harvester caused significantly more damage to the carrots than the top puller in both trials (Figure 23). In both trials, in excess of 50% of carrots were damaged during the Shear lifting operation. This level of damage was 5 times more than Top pulling. Furthermore, an increase in the level of damaged carrots was recorded at all sampling points during the Shear lifting operation, while most of the damage associated with Top pulling occurred between the shear and the web.

32% of carrots in the trial at Sassafras were damaged at the shear during Shear lifting. This level of damage was much higher than in the trial at FVRS (8%) (Figure 24). The preponderance of damaged carrots were broken in the trial at FVRS, indicating that modification to the shear settings was required. Adjustments to the shear of the Shear lifter reduced this level in the Sassafras trial (Figure 25). During the remainder of the Shear Lifting operation the increase in level of carrot damage was mainly associated with carrot splitting in the Sassafras trial and side damage and splitting at FVRS. The decrease in side damage and increase in broken carrots in the trial at Sassafras was most likely a result of the different webs used in the two trials (Baby web – FVRS; Ring web – Sassafras). Carrots with scruffy tops were a major problem identified in the Sassafras trial, however, they occurred mainly in the Shear lifting operation and were caused by the method of foliage removal rather than the harvester *per se*. Therefore, further consideration needs to be given to the mode of leaf removal if the shear lifting operation is going to be commercially refined and implemented.

Cracking was the predominant carrot fault recorded at the shear in Top pull harvesters, although this damage was only a minor component of the total damage for this machine and would have occurred prior to harvesting (Figure 24). Small levels of all other faults were recorded during the Top pulling operation.

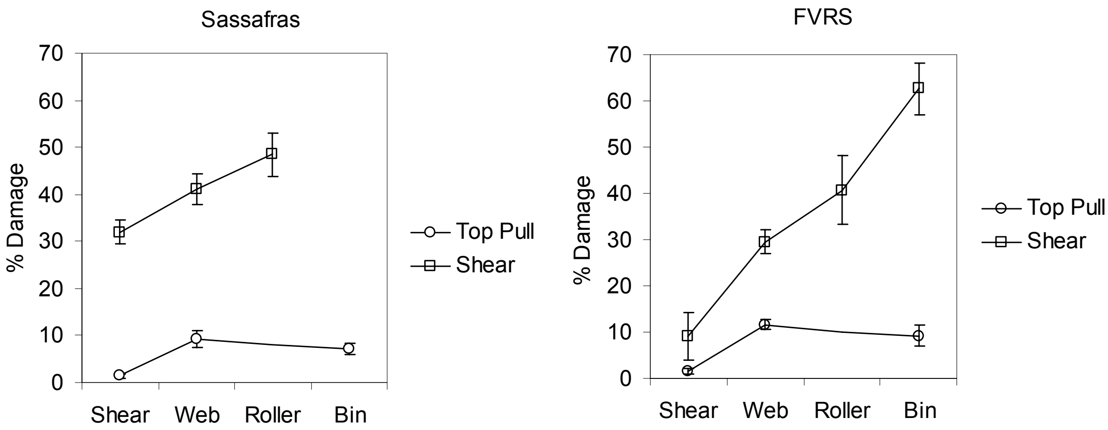


Figure 23. Percentage carrot physically damaged carrots at different points along the harvesting process after harvesting by top pulling (Top Pull) and shear lifting (Shear). NB carrots with scruffy tops are not included in this data. Bars represent SEM.

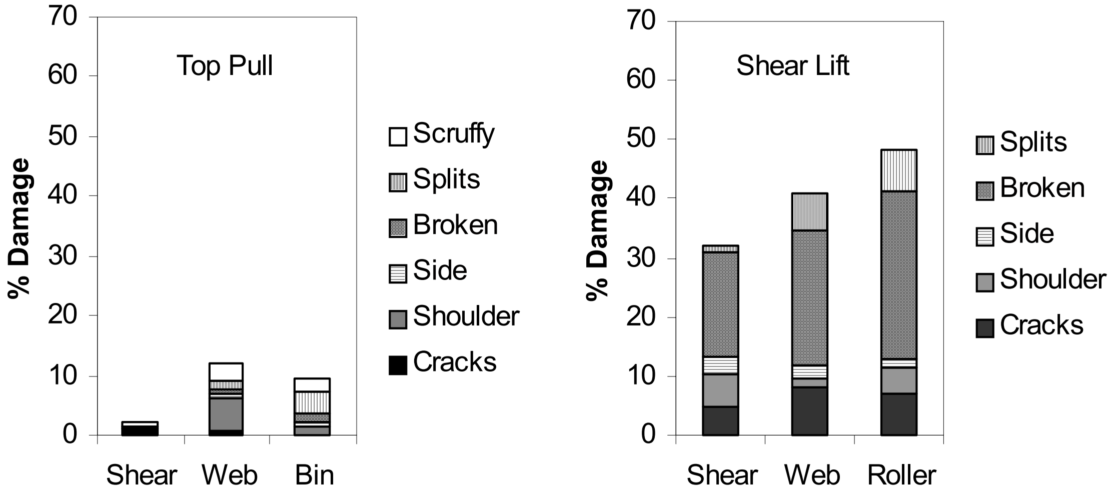


Figure 24. Percentage of carrots with specific faults at different points along the harvesting process; after top pulling (Top Pull) and shear lifting (Shear). Trial conducted at FVRS.

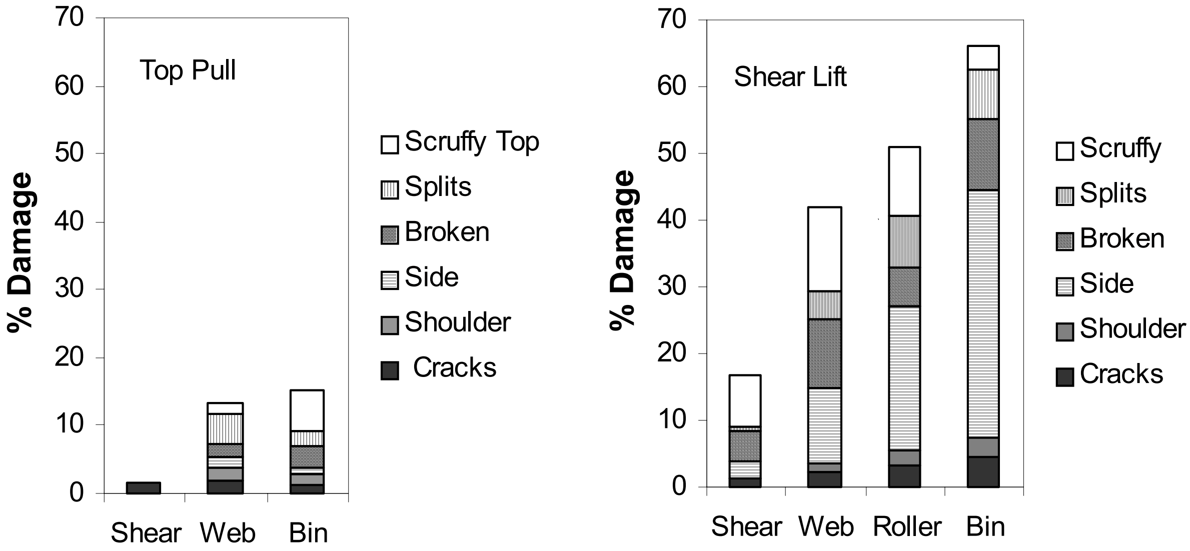


Figure 25. Percentage of carrots with specific faults at different points along the harvesting process; after top pulling (Top Pull) and shear lifting (Shear). Trial conducted at Sassafras.

Challenges and possible avenues for improvement to the shear lifting operation

- **Press wheel** An unknown proportion of damage could possibly be attributed to the press wheels sitting above the shear. The removal of these wheels may reduce the proportion of damage occurring at the shear, currently some 10-30%.
- **Web sizing** Web sizing appears to have an influence on the type and extent of damage created. Different web sizing or web designs may help to reduce damage.
- **Bin / box delivery** Further work on the delivery mechanisms to minimise damage during the transfer of carrots from the harvester to bins or box's is required to reduce 30% damage occurring at this stage.
- **Deeper shear / correct shear level** During both trials the shear lift operator experienced difficulty in setting the shear at an efficient depth. The operator suggested experimenting with a larger shear.
- **Soil**– Large volumes of soil could potentially be brought into the factory where operation of the shear lift harvester has been set to minimise carrot damage. This problem would be exacerbated where soil types are inappropriate or wet weather.
- **Top removal** – Use of a shear lift operation to harvest carrots is dependent on the ability to remove the tops of carrots less than 15mm above the crown. Use of a slasher is likely to cause significant damage as carrots crowns are normally at different heights above the relatively uneven soil surface. To some extent this problem may be alleviated by precision bed forming however a solution is more likely to lie in the development / sourcing of new machinery such as a carrot crowner or other equipment.

Root disturbance using horizontal shear

Brown and Gracie (2000) reported that carrots that were lifted slightly to detach fibrous roots from the taproot caused carrots tops to become flaccid, losing their susceptibility to splitting after one day. The authors used this to demonstrate the effect of water uptake on carrot splitting. Due to the inconsistent results associated with leaf trimming, further trials considered the effect of root disturbance as a mode of reducing carrot splitting propensity.

Methodology

Undercutting taproots using a root pruning shear (Figure 26) set at a depth of 300mm was examined as a method of reducing splitting. Two trials were undertaken at Forthside Vegetable Research Station comparing the splitting susceptibility of untreated control carrots with carrots that had were undercut the day prior to assessment. The trial was undertaken in a randomised complete block design, replicated three times. Carrot splitting susceptibility was recorded using the hand held penetrometer.

In addition to the undercutting trials the capacity of the conventional top-pulling harvester to harvest carrots with wilted leaves was assessed. This was achieved by hand lifting carrots slightly to break the connections between the taproot and the fibrous root system before allowing them fall back into the same hole several hours before mechanical harvesting. The treatments simulated the level of wilting noted following undercutting (Figure 27).

Results and Discussion

Splitting susceptibility of carrots at sunrise in the two undercutting trials are shown in Figure 28. In Trial 1 no significant difference in splitting susceptibility was recorded between carrots that had were undercut compared with the untreated control carrots. In the following trial (Trial 2) carrots were also lifted slightly by hand to break to free the taproot from the soil but allowed it to fall back into the same hole. In Trial 2 both hand lifting and mechanical undercutting significantly ($P<0.05$) reduced splitting propensity compared with untreated carrots. In Trial 2 the angle of the undercutting bar was altered slightly to produce a greater root disturbance. This change in undercutting mode would account for the different responses recorded between the two trials.

Attempts to mechanically harvest carrots with wilted leaves were ineffectual as the wilted leaves tended to slip off the cones before being taken up by the belt. The failure to mechanically harvest (by top pulling) wilted carrots following undercutting suggests that the undercutting technique has limited application. Furthermore, the flaccid carrot taproots would most likely require re-hydration following harvesting for them to be classified as premium grade. The disadvantages associated with undercutting impeded any further progress of the novel undercutting strategy.

Figure 26. Root pruning shear used to undercut carrots

Figure 27. Carrots plots 24 hours after undercutting (foreground) compared with untreated control plots (background)

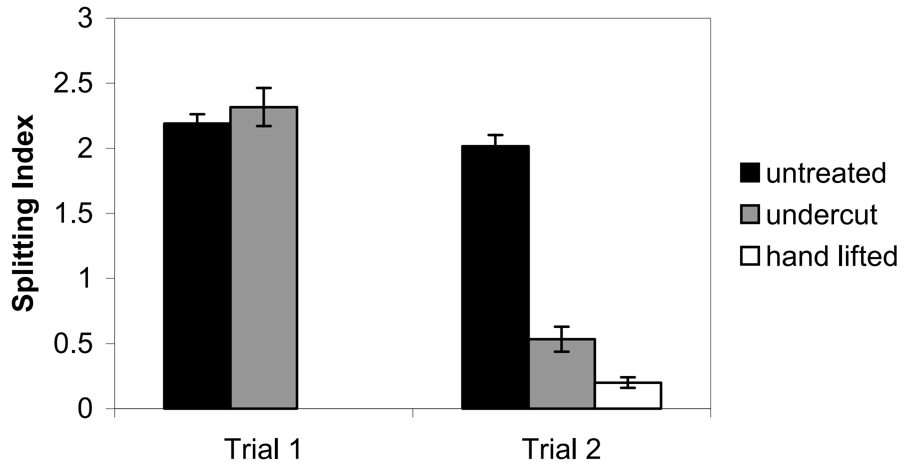


Figure 28. Splitting Index of carrots after undercutting (undercut), hand lifting (hand lifted) one day prior to assessment.

Minimising carrot shape defects and size variation

Carrots that retail for the highest prices fall within a stringent market specification for size and shape and must have the required colour, skin finish and blemish free status. While the management of plant diseases that influence carrot quality and yield has received much attention, very little attention has been given to non-pathogenic causes of reduced pack out, such as undesirable size and shape characteristics. A recent study completed by Brown and Gracie (2000) examining non-pathogenic causes of reduced packout provided some evidence that improved evenness of intra-row spacing between carrot plants at crop establishment has an impact in reducing the proportion of misshapen mature taproots as well as the variation in size. This section of the project sought to extend this preliminary work by bench marking the current precision of the seed drilling in commercial crops, and testing possible strategies to manipulate evenness of intra row seed placement as a way of controlling carrot shape and quality characteristics.

Survey of intra-row plant spatial distribution

An initial survey of commercial crops was undertaken to benchmark the evenness of the intra-row distance between adjacent seedlings as a measure of the precision of seed placement. In addition to the survey preliminary trials were also conducted to investigate the impact of seed size grading on drill seeding accuracy.

Methodology:

The precision of seed placement was analysed in this study using the widely accepted Spacing Index method as described by Kachman and Smith (1995). The spacing index categorises the size of a gap between adjacent seedlings within a row into one of three groups:

(1) 'TARGETS': gaps falling within an acceptable target range.

(2) 'MISSES': gaps larger than the target range.

(3) 'DOUBLES' gaps smaller than the target range.

In this study seeds were recorded as being on 'TARGET' when the distance between seedlings fell within 0.5 to 1.5 times the target spacing, 'MISSES' when the distance between seedlings was greater than 1.5 times the target spacing, and 'DOUBLES' when the distance between seedlings was less than 0.5 times the target spacing. For example, if the target spacing between seedlings is 40mm then all the gaps between 20-60mm in size are recorded as Target, gaps less than 20mm are doubles, and gaps greater than 60mm are misses.

In addition to this the mean spacing ($\overline{\mathrm{X}}$) was calculated.

$$\overline{\mathrm{X}} = \sum_{i=1}^{\mathrm{N}} \frac{\mathrm{X}i}{\mathrm{N}}$$

Where X_i is the distance between plant i and the next plant in the same row and N is the total number of distances measured (Kachman and Smith, 1995).

Eight commercially planted crops were examined in the survey; six of the crops were planted with *var.* Kuroda and two with *var.* Stefano. All the commercial crops assessed were planted in a 6-row configuration on raised beds. The distance between adjacent seedlings in the same row was measured using a tape measure. Three replicates of 30 measurements were taken from each of the six rows on a bed. Plant density (3-6 leaf stage) was also computed from this data. For some crops stand density was recorded again when they had reached harvest maturity.

In addition to the survey, a seed lot was graded into small (<1mm) and large (1-2mm) seed and planted at two separate sites. Seeds larger than 2mm were discarded. Spacing index measurements were also taken for these trials.

Results and Discussion

From the 8 crops surveyed, 40 to 70% of the intra row gaps between adjacent seedlings fell within the target spacing range (Figure 29). The average target index across of crops was approximately 50%. This level of precision is well below that recorded for corn, which generally attains a target index of 80% or greater (Agnes, and Luth, 1975). However, the data recorded in this study is more akin to levels of approximately 60% recorded for coated sugar beet seeds (Kachman and Smith, 1995).

Of the two carrot varieties surveyed, a lower seed placement accuracy was encountered with the var. Stefano (average target index = 43%) than var. Kuroda (average target index = 53%). However, the difference between the two cultivars was not statistically significant (P>0.05). Spacing that fell outside the target range were predominantly misses, i.e., spacings greater than the target range. This was the case for both cultivars (Table 1, Figure 29).

The low number of doubles and higher proportion of on target seed in crops 2 and 5 was most probably due to these measurements being taken later in the season after self thinning had taken place. The issue surrounding spacing index measurements early and late in crop development is discussed in more detail later.

Table 1. Mean seed drill spacing index (%) recorded in commercial crops sown with cv. Kuroda and cv. Stefano. No significant difference between cultivars was recorded.

Crop	Target	Miss	Double
CC0-018	50.1%	36.4%	14.7%
Stefano	43.1%	38.3%	18.6%

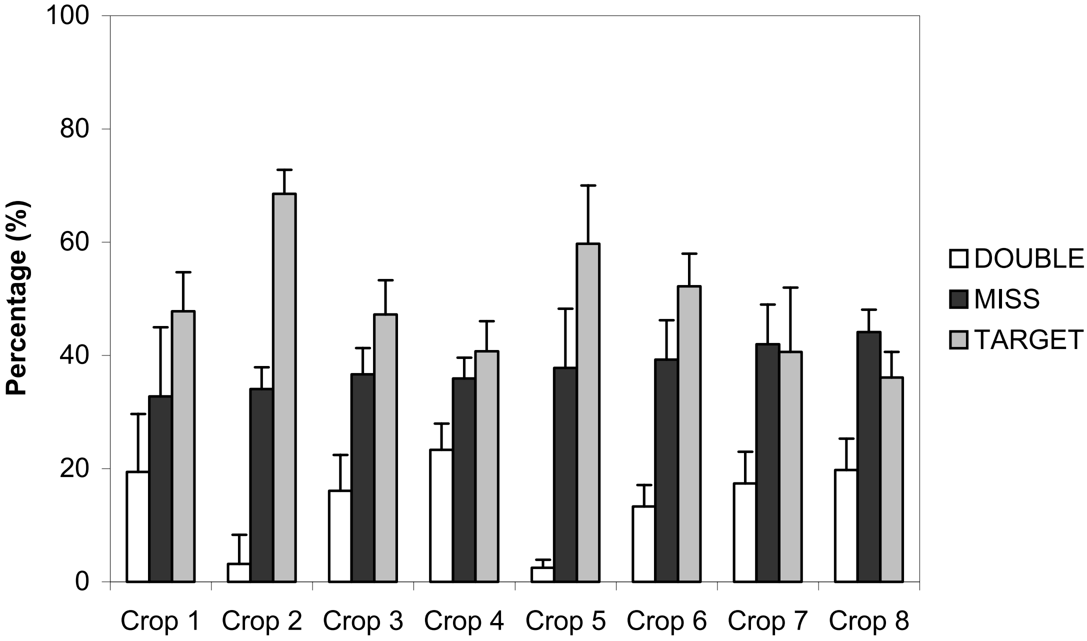


Figure 29. Spacing Index measurements. Proportion of doubles, targets, misses for eight separate commercial crops; var. Kuroda (Crops 1-6) and var. Stefano (Crops 7&8). Bars represent SEM.

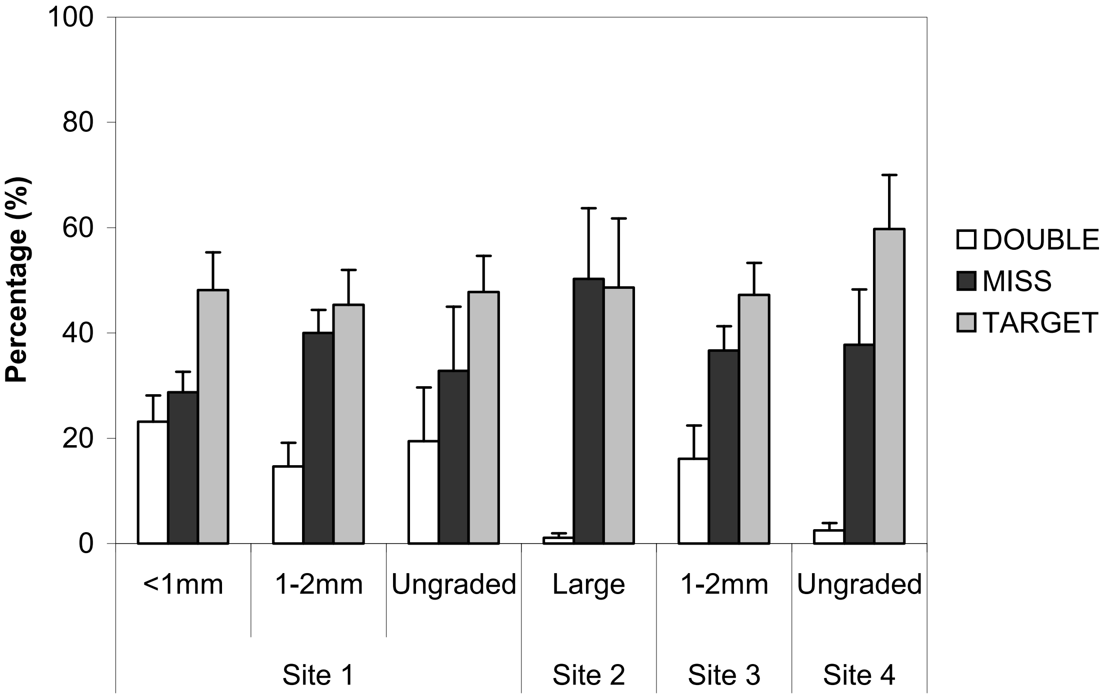


Figure 30. Spacing Index measurements. Proportion of doubles, targets, misses for graded and ungraded carrot seed lots. All trial sites were planted with var. Kuroda. Bars represent SEM.

Effect of seed size grading on spacing index and stand density

Grading of a seed lot (var. Kuroda) into two sub seed lots based on size, <1mm and 1-2mm, did not significantly improve the proportion of seeds that fell within the target spacing range, when compared with an ungraded seed lot (Figure 30). However, a higher level of gaps classified as misses and a lower proportion of doubles were recorded for the larger seeds (1-2mm) than the small (<1mm) ($p=0.05$). The increased level of gaps classified as misses from planting seeds 1-2 mm in size presumably also resulted in a reduced plant density for this size class (Figure 30). Conversely, the smaller seeds produced a higher proportion of doubles than the 1-2mm class ($P=0.05$) and the ungraded seeds, however, this latter difference was not statistically significant ($P>0.05$).

Although seed lot grading did not improve the proportion of seeds placed within the desired target range, the reduced level of seeds planted close together, classified as doubles, may be advantageous as increased sowing rates may be adjusted to account for the reduced density. Furthermore a reduction in doubles may lead to improved establishment and an increase in class 1 pack out due to a reduction in misshapen carrots.

Spacing Index and Density measurements taken at early and late stages of crop development

The average spacing index was found to change as crops approached maturity. The percentage of plants on target increased with crop maturity in all five crops monitored at an early and late stage of development ($p=0.05$) (Figure 31). A large proportion of this increase was due to a concomitant decrease in doubles in four of the five crops ($P=0.05$). This decrease in doubles was most likely due to self thinning, or the pushing apart of plants that germinated close together. In general the proportion of misses remained constant with the exception of the Forthside crops where the number of misses dropped ($p=0.05$). This decrease in misses can only be explained by late emergence or sampling error.

The density measurements available for this analysis were not sufficient to determine if density dropped during this period however this is likely. The data collected suggests that plant density and ASI measurements should be taken at a uniform crop age.

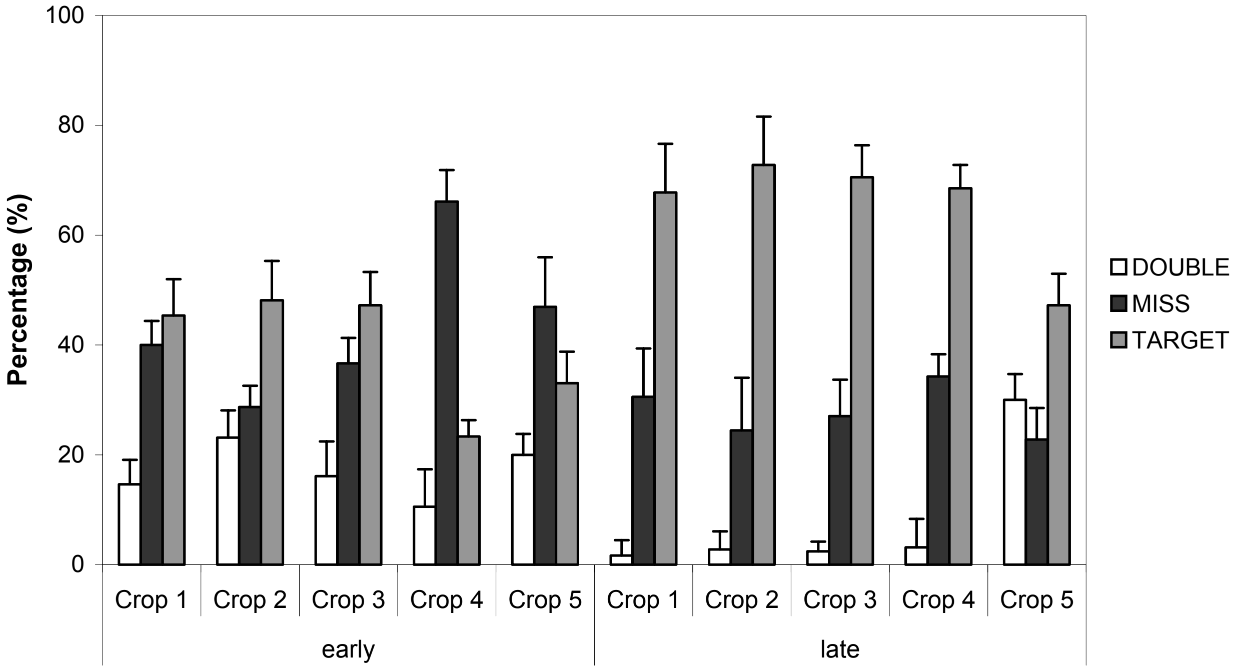


Figure 31. Spacing Index measurements. Proportion of doubles, targets and misses measured at early and late stages of crop development. Crops 1-4 are var. Kuroda and crop 5 contains var. Stefano.

Major outcomes from the survey and preliminary trials were:

- var.Kuroda and var. Stefano plant densities were, in general, below that expected for establishment.
- Drill accuracy was below the acceptable spacing index (proportion within the target range) of other vegetable crops, with only approximately 50% of gaps between seedlings falling within the target range.
- Seed size grading affected the proportion of spaces between seedling falling within the target range, however larger seeds (1-2mm) generally produced less doubles, and more misses when compared with seed <1mm in size. It is possible that a reduction in doubles may lead to improved establishment and an increase in class 1 pack out due to a reduction in misshapen carrots. This requires further research as it is unclear whether the increased level of misses was due to lower germination levels or a seed by drill interaction.
- Plant density decreased between establishment and maturity. Self-thinning as the crop aged resulted in a reduction of doubles (most likely due to competition) and a corresponding increase in target spacing. It is however, acknowledged that it is difficult to accurately measure spaces between the mature plants.

Effect of planting configuration on crop development and pack out in 2001/02

The planting arrangement in the above commercial crop survey as well as the preliminary trial consisted of 3 double rows (total of 6) on 1.2m wide raised beds. The following experimental work investigated how alterative planting configurations impact on crop development, pack out and yield.

Methodology

The effects of four separate planting configurations on carrot yield and pack out were examined at three separate sites; two at Sassafras and one at Forthside. Each planting configuration was replicated 3 times at each site in a randomised complete block design. Each plot consisted of a 1.2m wide x 10m long raised bed. Seeds were drilled (Stanhay Singulaire 750) at a target distance of 40mm apart along rows, except for the middle of 3 double rows, which were planted at a target spacing of 60mm apart. The four configurations assessed were:

4 single rows: |←*150*→|←*420*→|←*150*→|

5 single rows: |← *150*→|←*200*→|←*200*→|←*150*→|

6 single rows: |←*150*→|←*200*→|←*150*→|←200→|←*150*→|

3 double rows: |←*75*→|←350→|←*75*→|←*350*→|←*75*→|

[*Values between lines denote the distance (in millimetres) between planted rows on a bed*]

The planting density measurements were recorded following trial establishment and carrots were destructively harvested from 1m^2 quadrats 90, 100, 120 days after planting (DAP). Class 1 pack out, taproot size distribution, major faults and fresh and dry weight of foliage and taproots were recorded. However, given that 120 DAP equated to commercial harvest, only the data collected on this date was analysed and detailed in this report. Machinery drilling problems were encountered whilst sowing the 3-double treatment at Forthside. This treatment was therefore excluded from the analysis of this trial.

Results and Discussion

The effect of planting arrangement on the total yield of carrot taproots, expressed on a fresh weight basis, harvested 120 days after planting is shown in Figure 32. Higher yields were achieved with increasing number of rows planted on the bed. Yields recorded were in the following order of magnitude 6 single > 3 double > 5 single > 4single. At the 95% confidence limit significantly higher yields were recorded at both the 3 double and 6 single row arrange than the 4 single row arrangement.

Care should be taken when interpreting the increase in gross yield as an attribute of arrangement alone, as it may in instead be a reflection of stand density. A positive correlation between planting density and gross yield was recorded as evidence that the yields recorded were a reflection of stand density and not planting configuration, however, it is difficult to separate the independent effect of the two variables, density and arrangement, in this trial.

The proportion of Class 1 carrots was also determined for each of the treatments (Figure 33). In this experiment Class 1 pack out was high and the average pack out for the different configurations ranged from 87 to 92%. No significant difference ($P<0.05$) was recorded between treatments. Hence the yield of Class 1 carrots is a direct reflection of the gross yield achieved.

Class 1 carrots were also size graded by diameter into four separate categories; undersized, small, medium and large. Only approximately 3-5%, by weight, of carrots were undersized and therefore the level falling into this size grade was not significantly affected by the planting configuration. Medium sized carrots are viewed as the optimal marketing size class and the highest proportion of carrots falling into this category occurred in the 4 single row arrangement (48%).

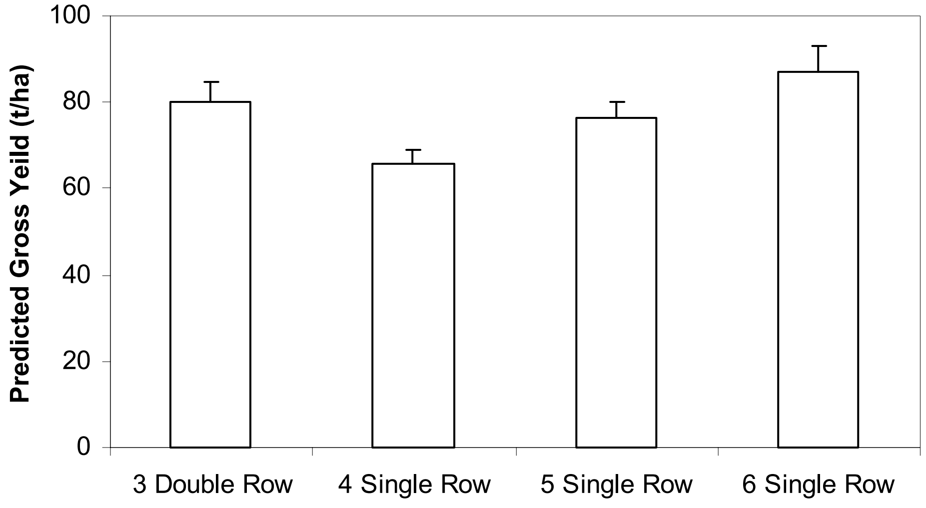


Figure 32. Gross yield (t.ha^{-1}) of carrot taproots planted in four different plant configurations. The values shown are the means across three trial sites. Bars represent SEM.

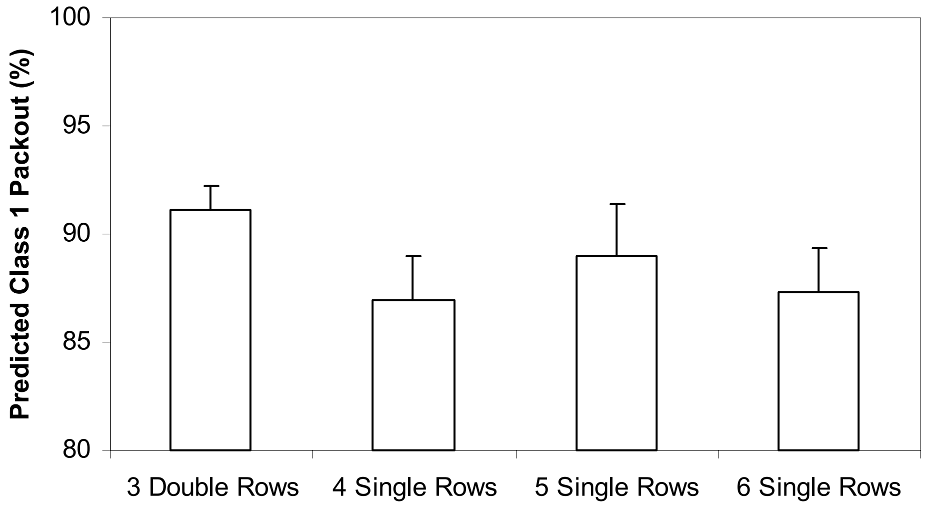


Figure 33. Class 1 yield (t.ha^{-1}) of carrot taproots planted in four different plant configurations. The values shown are the means across three trial sites. Bars represent SEM.

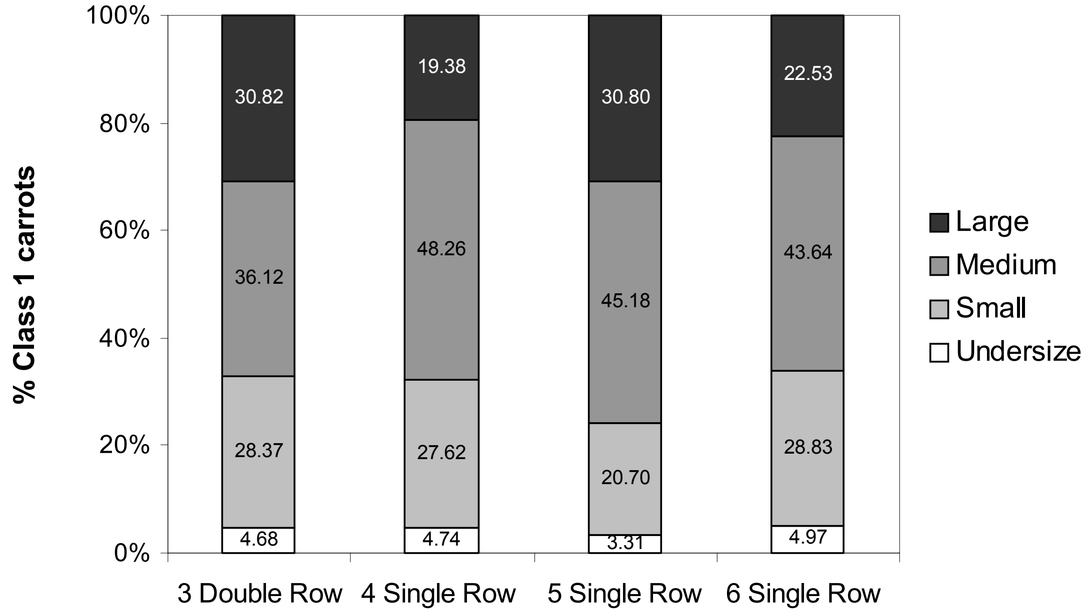


Figure 34. Proportion of Class 1 carrots in each of the size classes based on shoulder diameter; undersized, small, medium and large.

Effect of planting configuration, stand density, genotype and planter on spacing index, carrot size distribution and quality in 2002/03

Three trials were undertaken at Forthside Vegetable Research Station to examine the effect of carrot variety, seed size grading, type of planter and planting arrangement on spacing index and subsequent taproot shape and quality parameters.

Trial 1 planted on the 3rd October 2002

Trial 2 planted on the 14th November 2002

Trial 3 planted on the 22nd January 2003.

Methodology

Trial 1: planted 3rd October 2002

The first carrot variety trial was planted at Forthside Vegetable Research Station on the 3rd October 2002. 27 beds 36 meters in length were divided in half to create 54 separate plots, which were 18m long x 1.2m wide. Eight different carrot varieties were planted with a Stan-Hay Precision drill (Stanhay Singulaire 750), equipped with 96 hole disks set at E24, which corresponded to a 45.9mm spacing between seeds. The carrot variety trial was planted amongst drill configuration research. In total, 24 plots were used for the carrot variety trial since each variety was planted in separate plots that were chosen at random.

The varieties sown were:

- CAR 217
- CAR 219
- STEFANO
- MOJO
- KENOBI
- AMA
- KADOMA
- KURODA (seed size 1.6-2mm)

As mentioned above a drill configuration experiment was integrated with the aforementioned variety trial. This was undertaken to avoid repetition since some treatments were common to both trials. Two carrot varieties (Kuroda and Stefano) and two carrot seed sizes of cv. Kuroda (1.6-2.0mm and 2.0-2.4mm) were assessed in the configuration trial. The Stan-Hay precision drill was used and set at cog configurations, F17, E24, D30, corresponding to approximately 35, 40, and 45 mm respectively between seeds. Three replicates were planted for each of the three seed lots (1. Stefano ungraded; 2. Kuroda 1.6-2.0mm; and 3. Kuroda 2.0-2.4mm) at each of the three configurations. A total of 27 plots were planted for the drill configuration trial.

Trial 2: Planted 14th November 2002

The second trial was also planted at Forthside Vegetable Research Station, on the 14th November 2002. Similarly, 27 beds, 36 metres in length were halved in length to form a total 54 plots that where 18m long x 1.2m wide. A carrot variety and drill configuration trials were planted, but due to adverse weather conditions affecting the trial only the outcomes from the variety trial are discussed.

The following 11 varieties were planted in a randomised design consisting of 3 replicates:

- Kuroda (seed size 1.6-2mm)
- STEFANO
- STEFANO – P
- MOJO
- CRF
- CLX 3175
- JTC
- KADOMA
- KENOBI
- CAR 217
- CAR 219

Trial 3: Planted on the 22nd January 2003

Two precision air drills, a Stanhay Singulaire 750 and Accord Miniair S, were compared in a configuration trial consisting of either 4 or 5 rows per bed sown at three-target seedling spacings (35, 40, 45mm). The following configurations were assessed using cv. Kuroda (seed size: 1.6-2mm):

- 4 rows/bed, using Stan-Hay set at 35, 40 and 45mm spacing.
- 4 rows/bed, using Accord set at 35, 40 and 45mm spacing.
- 5 rows/bed, using Accord set at 35, 40 and 45mm spacing.

Each configuration was replicated three times resulting in a total of 27 treatments. Each treatment was planted on a raised bed 1.2 m wide and 18 m long.

Accord drill

The following manufacturers specifications where employed to set the Accord drill (disc 8008) to the required seed spacing:

Cog Configuration	approx. Seed Spacing
19-17-23	35mm
19-19-23	40mm
17-19-23	45mm

Stan-Hay drill

The following manufacture specifications where employed to set the Stan-Hay (48 hole disc) at the target seed spacing:

Cog configuration	approx. Seed spacing
F17	35mm
B24	40mm
E24	45mm

Variety Trial

In addition to the above configuration trail, seven carrot varieties were planted at set configurations, chosen on the bases of previous results and observations. The trial was sown using the Stan-Hay Precision drill at the following seed spacings:

- Kadoma – set at 35, 40 and 45 mm seed spacing
- Stefano – set at 35, 40 and 45 mm seed spacing
- MOJO – set at 35, 40 and 45 mm seed spacing
- CAR 217 – set at 45 mm seed spacing
- CAR 219 – set at 45 mm seed spacing
- HCR 4 – set at 45 mm seed spacing
- HCR 5 – set at 45 mm seed spacing
- HCR 6 – set at 45 mm seed spacing

Each treatment was replicated 3 times and consisted of 1.2m wide x 18m long section of raised bed. As with all trials, the treatments were randomly allocated to the plots in a randomised complete block design. The only exception to this was the sowing of *var.* HCR 5 and HCR 6 in the buffer zones between each block for observational purposes.

Data collated

The method of data collection was consistent for the three trials planted in 2002/03. Evenness of seed spacing (spacing index) and stand density measurements were recorded approximately 40 days after sowing. Later in crop development, as the carrot taproots approached harvest maturity, taproot shape characteristics, yield, and quality parameters were assessed.

Stand density: A 55.5 cm x 1.8 m quadrant was placed along a row within a plot and the number of carrots growing within the quadrant boundaries were counted to obtain the density of seedlings established per unit area. This measure of plant density was repeated three times within each plot. Given that three replicates were planted for each treatment a total of 9 density readings were recorded for each treatment.

Spacing Index: The distance between adjacent carrot seedlings in the same row was measured in order to calculate the Spacing Index (targets, misses, doubles) (as outlined above on page 49). The distance between adjacent carrot plants within a row was recorded for 30 consecutive gaps 3 times (total of 90 measurements). This was undertaken for every row within each plot. The rows were assigned a code for identification according to whether they were outside or inside rows, so that individual rows on a bed were monitored. Given that each treatment was replicated three times a total number or measurements per treatment were: 90 per row x number of rows (4, 5) x 3 replicates. This was undertaken for both the variety and configuration trials.

Carrot harvest quality and yield: Carrots were sampled from each plot by harvesting all the taproots from a quadrant, 0.185m x 1.8 m in size, per plot. Duplicate samples were taken from each plot and were later combined with the three treatments replicates, i.e. a total of 6 quadrates were pooled for each treatment. The harvested samples were transported to the laboratory where they were washed in a rotating barrel and later size graded and weighed. All carrots with faults, preventing them from being classed as Class 1 quality, were sorted into groups according to the type of fault present. The fresh weight of carrot in each of the fault groupings was recorded. The data were analysed to obtain yield, size distribution, % faults and estimated pack out for each variety/drill configuration.

Class 1 size grading: All Class 1 quality carrots were size graded by shoulder diameter. Nantes varieties were graded into 5 size ranges; <25mm, 25-30mm, 30-40mm, 40-44mm and >44mm, and Kuroda varieties were size graded into 4 size ranges; <30mm, 30-40mm, 40-50mm, >50mm. The roots within each of the size ranges were also categorised according to the degree of rounding of the root tip; tapered, rounded or domed. The definitions of these categories are described later (page 86). The proportion of carrots in each category and sub category is presented as a fresh weight basis.

Results and Discussion

Spacing Index

In Trial 1 the effect of seed size and spacing arrangement on the intra-row seedling spacing (Spacing Index) and the ensuing marketable yield was examined for *var.* Kuroda seeds graded into size classes 1.6-2.0mm and 2.0-2.4mm and a *var.* Stefano ungraded seed lot. All three seed lots were planted in a 4-row arrangement at three target spacings between seedlings. The target spacings were:

35mm inner rows and 40mm outer rows (abbreviated 35/40)

45mm inner rows and 50mm outer rows (abbreviated 45/50)

55mm inner rows and 60mm outer rows (abbreviated 55/60)

The relationship between the target spacing and the actual mean intra row spacing achieved for this trial is shown in Figure 35. The dotted line on the graph denotes a 1:1 relationship. The figure illustrates a large variation in 'actual spacing' recorded at each 'target spacing', even though each point is a mean of 30 measurements. This large variance was unexpected and it was difficult to ascertain at first observation whether it was due to field factors (e.g. soil condition), seed lot vigour, drill errors, or more likely, a combination of these possible sources of variance.

The data in Figure 35 are represented in Figure 36, except this time each point is a mean of 270 (30 x 9) individual gap measurements. A linear regression analysis between the target and mean spacing achieved was performed. The further exploration of the data revealed a weak relationship between the two variables ('actual' vs 'target' spacing), however, more enlightening, the slope of the linear regression was approximately 0.48 (Figure 36). The slope recorded (0.48) most likely reflects inaccuracy associated with accuracy of the drill as opposed to seed lot performance. Conceptually, the slope of the linear regression is largely influenced by the number of seeds planted per length of bed (i.e., planter settings or seed x planter interaction) while the intercept is influenced by seed lot performance (i.e., % seedling emergence).

The relevance of the Spacing Index values given in Tables 2-5 is expounded upon in greater detail below. Suffice to say at this point that the mean level of targets across all treatments was approximately 45%, and the Kuroda large sized seeds (2.0-2.4mm) resulted in higher proportion of targets than the medium sized seed (1.6-2.0mm), consistent with observations recorded in the above survey. However, the difference between the two graded seed lots was only about 3% and was not significantly different at the 95% confidence limit (Tables 4 and 5). Given that target stand densities were not achieved and statistical analysis of the emergence data revealed no major differences in plants precision between treatments (Tables 2-5) the harvest data are not presented in this report.

The second component of the experiment planted on the 3rd October 2002 (Trial1) consisted of a variety trial. All varieties were planted in the in a 4 row configuration with the two inner rows planted at a target density of 45mm and the two outer rows at 50mm. Spacing index calculations are shown in Tables 6 and 7.

Spacing Index was calculated for each row in the 4 row planting arrangement. Since the inner rows were planted at a lower density than the outer rows the trial was analysed as a split plot design with seed lot as the main plots and inner and outer rows sub plots (Tables 6 and 7). When analysing the effect of density the inner and outer rows were examined separately (Tables 2 and 3, 4 and 5).

A significant difference ($P<0.05$) in the mean spacing between seed lots sown at the same target density, 45mm/50mm intra spacing in the inner/outer rows, was recorded (Table 6). From this data it is not possible to ascertain if the differences in stand density, as indicated by the mean spacing, between seed lots (Table 6) was due to differences in seed lot quality (percent germination, emergence etc) or a seed lot by drill interaction affecting the number of seeds sown per unit length of bed.

Initially, Spacing Index classes of doubles, targets, and misses were calculated based on target spacing in accordance with International standards (Kachman and Smith, 1995) (Table 2,3 & 6). Given that a significant difference ($P<0.05$) in intra row seedling density between seed lots was recorded (Table 6), any difference in Spacing Index recorded between seed lots based on the conventional method may be a reflection of the stand density achieved and not a change in seedling distribution around a mean value. Hence, ascribing differences in Spacing Index (i.e., %doubles, targets and misses) to drill planting precision when the mean spacing is not the same for the seed lots being compared can in fact be a misinterpretation, leading to erroneous conclusions being drawn. For this reason Spacing Index calculations were also determined based on the mean spacing recorded for each plot (Table 4, 5 & 7). The calculations were similar, i.e., 'doubles' were gaps less than 0.5 times the mean spacing, gaps on 'target' ranged from 0.5 to 1.5 times the mean value, and 'misses' were gaps 1.5 greater than the mean spacing.

Spacing Index calculations based on target spacing revealed a significant difference in the proportion of MISSES between seed lots (Table 6), however a significant positive correlation ($P<0.001$) between %miss and mean spacing was recorded as evidence that this result was a direct reflection of seedling density achieved and not a change in distribution of intra row gap sizes around a mean value. Hence, Spacing Index computed on the basis of mean spacing eliminates any bias associated with changes in density and any difference between seed lots that ensues is a reflection of the change in distribution of gap sizes around a mean value. In the above example, no significant difference ($P>0.05$) in %misses between seed lots was recorded when calculated based on this latter computation (Table 7). This outcome justifies the calculation of Spacing Index based on the 'mean spacing' as opposed to the standard' target spacing' under these circumstances.

Overall, large differences in stand density were recorded across the different varieties examined at crop established. Unfortunately it cannot be ascertained from this data set whether the differences in stand density was associated with seed lot performance or a function of the seed by drill interaction influencing the proportion of seeds planted per unit area. Adjustments to the Spacing Index to account the differences in stand density revealed no major differences in the distribution pattern (misses, targets and doubles) between treatments.

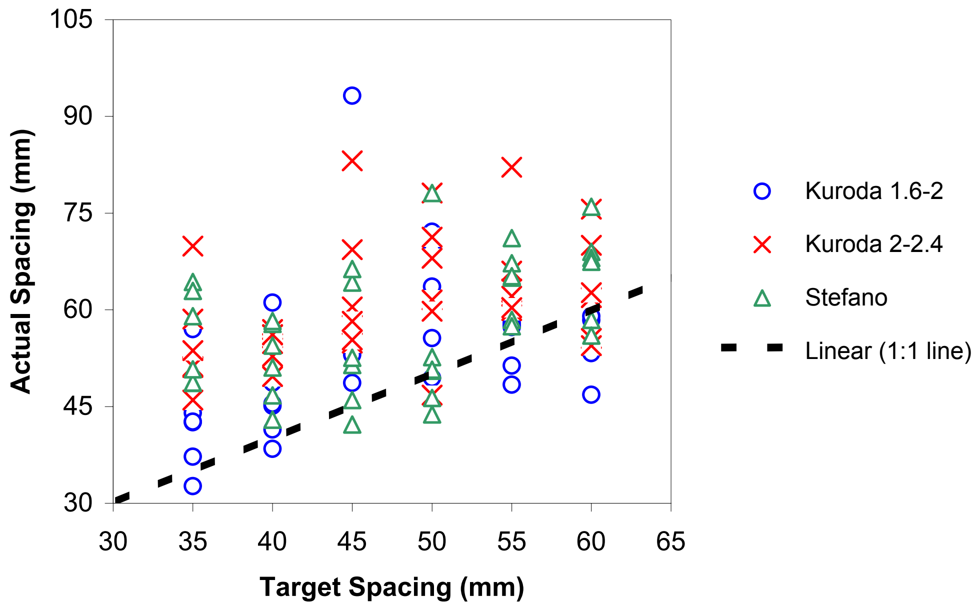


Figure 35. Relationship between target intra-row spacing and actual intra row spacing achieved for cultivars Kuroda and Stefano. Two seed sizes were examined (1.6 – 2mm and 2 – 2.4mm) for var. Kuroda based on size grading. Each point represents the mean distance between seedlings for 30 consecutive spacings. Dashed line represents 1:1 relationship.

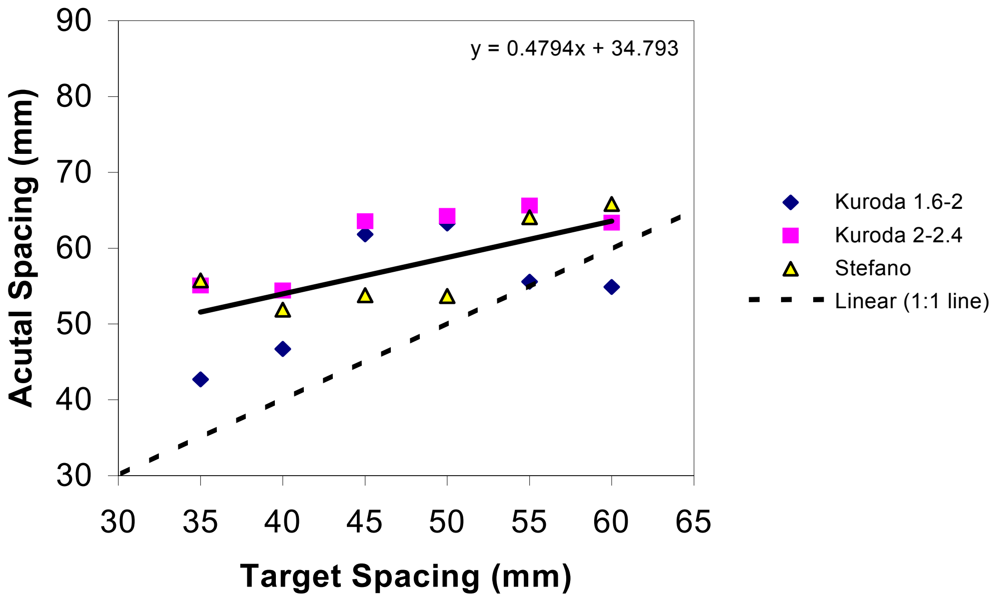


Figure 36. Relationship between target intra row spacing and actual intra row spacing achieved for cultivars Kuroda and Stefano. Two seed sizes were examined (1.6 – 2mm and 2 – 2.4mm) for var. Kuroda based on size grading. Each point represents the mean distance between seedlings for three replicates and each replicate consisted of 90 measurements. Solid line represents linear regression and dashed line represents 1:1 relationship.

Table 2. Percentage intra row seedling spaces classified as double, target and miss based on ***TARGET SPACING****. Data shown for seed lots planted at 35, 45 and 55mm target spacing in the outer rows of a 4 row arrangement.*

Seed lot	DOUBLE	TARGET	MISS	MEAN (mm)
Kuroda 1.6-2	30.3%	42.7%	27.0%	53.4
Kuroda 2-2.4	22.6%	45.2%	32.2%	61.4
Stefano	27.9%	41.2%	30.9%	57.9
LSD (p=0.05)	*5.8%*	*ns*	*3.6%*	*ns*

Spacing	DOUBLE	TARGET	MISS	MEAN (mm)
35 mm	19.1%	47.6%	33.3%	51.2
45 mm	32.9%	36.6%	30.5%	59.7
55 mm	28.8%	44.9%	26.3%	61.8
LSD (p=0.05)	*5.8%*	*4.7%*	*3.6%*	*7.4*

Spacing	**Seed lot**	DOUBLE	TARGET	MISS	MEAN (mm)
35	Kuroda 1.6-2	24%	49%	27%	42.7
35	Kuroda 2-2.4	13%	52%	35%	55.1
35	Stefano	21%	42%	37%	55.7
45	Kuroda 1.6-2	35%	34%	31%	61.8
45	Kuroda 2-2.4	27%	41%	33%	63.5
45	Stefano	37%	35%	28%	53.8
55	Kuroda 1.6-2	32%	45%	23%	55.6
55	Kuroda 2-2.4	28%	43%	29%	65.6
55	Stefano	26%	46%	27%	64.1
	LSD (p=0.05)	*ns*	*ns*	*ns*	*ns*

Table 3. Percentage intra row seedling spaces classified as double, target and miss based on ***TARGET SPACING****. Data shown for seed lots sown at target spacings of 40, 50 and 60mm in the inner rows of a 4 row arrangement.*

Seed lot	DOUBLE	TARGET	MISS	MEAN (mm)
Kuroda 1.6-2	27.3%	49.5%	23.2%	54.9
Kuroda 2-2.4	21.9%	51.0%	27.0%	60.7
Stefano	25.5%	48.4%	26.1%	57.1
LSD (p=0.05)	*ns*	*ns*	*ns*	*ns*

Spacing	DOUBLE	TARGET	MISS	MEAN (mm)
40 mm	19.4%	53.1%	27.5%	51.0
50 mm	30.1%	42.5%	27.4%	60.4
60 mm	25.2%	53.3%	21.5%	61.4
LSD (p=0.05)	*4.4%*	*6.3%*	*ns*	*7.7*

Interaction

Spacing	**Seed lot**	DOUBLE	TARGET	MISS	MEAN (mm)
40	Kuroda 1.6-2	23.5%	52.0%	24.4%	46.7
40	Kuroda 2-2.4	15.6%	55.9%	28.5%	54.4
40	Stefano	19.1%	51.5%	29.4%	51.9
50	Kuroda 1.6-2	29.1%	42.6%	28.3%	63.2
50	Kuroda 2-2.4	25.2%	45.7%	29.1%	64.3
50	Stefano	35.9%	39.3%	24.8%	53.7
60	Kuroda 1.6-2	29.3%	53.9%	16.9%	54.9
60	Kuroda 2-2.4	25.0%	51.5%	23.5%	63.4
60	Stefano	21.5%	54.4%	24.1%	65.8
	LSD (p=0.05)	*ns*	*ns*	*ns*	*ns*

Table 4. Percentage intra row seedling spaces classified as double, target and miss based on ***MEAN SPACING MEASURED****. Data shown for seed lots sown at target spacings 35, 45 and 55mm in the outer rows of a 4 row arrangement.*

Seed lot	DOUBLE	TARGET	MISS
Kuroda 1.6-2	33%	45%	22%
Kuroda 2-2.4	30%	48%	21%
Stefano	31%	47%	21%
LSD (p=0.05)	*ns*	*ns*	*ns*

Spacing	DOUBLE	TARGET	MISS
35	32%	47%	21%
45	34%	45%	21%
55	29%	49%	22%
LSD (p=0.05)	*ns*	*ns*	*ns*

Interaction

Spacing	**Seed lot**	DOUBLE	TARGET	MISS
35	Kuroda 1.6-2	36%	43%	21%
35	Kuroda 2-2.4	30%	49%	21%
35	Stefano	31%	48%	21%
45	Kuroda 1.6-2	34%	44%	22%
45	Kuroda 2-2.4	32%	49%	19%
45	Stefano	36%	42%	22%
55	Kuroda 1.6-2	31%	46%	23%
55	Kuroda 2-2.4	29%	47%	24%
55	Stefano	27%	52%	20%
	LSD (p=0.05)	*ns*	*ns*	*ns*

Table 5. Percentage intra row seedling spaces classified as double, target and miss based on ***MEAN SPACING MEASURED.*** *Data shown for seed lots sown at target spacings of 40, 50 and 60mm in the inner rows of 4 row arrangement.*

Seed lot	DOUBLE	TARGET	MISS
Kuroda 1.6-2	35.4%	41.8%	22.8%
Kuroda 2-2.4	32.8%	46.5%	20.7%
Stefano	34.0%	43.6%	22.4%
LSD (p=0.05)	*ns*	*ns*	*1.6%*

Spacing	DOUBLE	TARGET	MISS
40 mm	32.9%	46.0%	21.1%
50 mm	36.5%	42.0%	21.4%
60 mm	32.7%	44.0%	23.4%
LSD (p=0.05)	*ns*	*ns*	*1.6%*

Interaction

Spacing	**Seed lot**	DOUBLE	TARGET	MISS
40 mm	Kuroda 1.6-2	33.0%	46.3%	20.7%
40 mm	Kuroda 2-2.4	31.1%	49.6%	19.3%
40 mm	Stefano	34.6%	42.0%	23.3%
50 mm	Kuroda 1.6-2	39.1%	38.1%	22.8%
50 mm	Kuroda 2-2.4	34.1%	46.3%	19.6%
50 mm	Stefano	36.5%	41.7%	21.9%
60 mm	Kuroda 1.6-2	34.1%	40.9%	25.0%
60 mm	Kuroda 2-2.4	33.1%	43.7%	23.1%
60 mm	Stefano	30.7%	47.2%	22.0%
	LSD (p=0.05)	*ns*	*ns*	*2.8%*

Table 6. Percentage intra row seedling spaces classified as double, target and miss based on ***TARGET SPACING****. Data shown for seed lots planted at 40 and 45 mm in the outer at inner rows respectively of a 4 row arrangement.*

Bedrow	DOUBLE	TARGET	MISS	MEAN (mm)
inner rows	30.3%	43.4%	26.3%	59
outer rows	31.7%	38.3%	30.0%	58
LSD (p=0.05)	*ns*	*1.9%*	*2.3%*	*ns*

Seed lot	DOUBLE	TARGET	MISS	MEAN (mm)
AMA	3.5%	43.3%	53.2%	111.8
CAR217a	36.9%	41.9%	21.2%	48.2
CAR219b	31.8%	39.8%	28.4%	57.2
Kuroda 1.6-2	32.1%	38.4%	29.4%	62.5
Kuroda 2-2.4	26.0%	43.1%	30.8%	63.9
Kuroda >2.4	33.9%	37.3%	28.8%	55.5
Kuroda <1.6	32.7%	38.0%	29.4%	57.5
Kadoma	27.3%	47.8%	24.9%	54.5
Kenobi	38.4%	41.6%	20.0%	45.8
Mojo	33.1%	41.7%	25.3%	52.8
Stefano	36.3%	37.1%	26.6%	53.7
LSD (p=0.05)	*7.5%*	*ns*	*8.0%*	*14.2*

Interaction

Bedrow	**Seed lot**	DOUBLE	TARGET	MISS	MEAN (mm)
inner	AMA	5%	40%	55%	123.3
inner	CAR217a	36%	45%	19%	48.2
inner	CAR219b	33%	41%	26%	56.1
inner	Kuroda 1.6-2	29%	43%	28%	63.2
inner	Kuroda 2-2.4	25%	46%	29%	64.3
inner	Kuroda >2.4	30%	42%	28%	58.4
inner	Kuroda <1.6	30%	44%	26%	57.0
inner	Kadoma	26%	52%	22%	54.5
inner	Kenobi	40%	41%	19%	44.2
inner	Mojo	34%	43%	23%	52.8
inner	Stefano	36%	39%	25%	53.7
outer	AMA	2%	46%	51%	100.3
outer	CAR217a	37%	39%	24%	48.3
outer	CAR219b	31%	39%	31%	58.3
outer	Kuroda 1.6-2	35%	34%	31%	61.8
outer	Kuroda 2-2.4	27%	41%	33%	63.5
outer	Kuroda >2.4	38%	32%	30%	52.5
outer	Kuroda <1.6	35%	32%	33%	57.9
outer	Kadoma	28%	44%	28%	54.5
outer	Kenobi	37%	42%	21%	47.4
outer	Mojo	32%	41%	28%	52.9
outer	Stefano	37%	35%	28%	53.8
	LSD p=0.05	*9%*	*ns*	*ns*	*ns*

Table 7. Percentage intra row seedling spaces classified as double, target and miss based on ***MEAN SPACING MEASURED****. All plots were sown at target spacings of 45mm & 50mm in outer and inner rows respectively of a 4 row arrangement.*

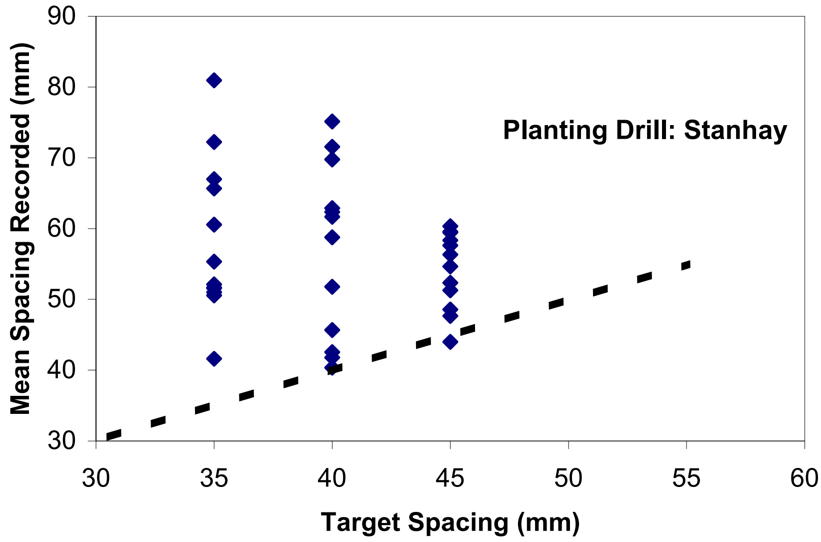
Bedrow	DOUBLE	TARGET	MISS
inner rows	34%	45%	21%
outer rows	33%	46%	21%
LSD p=0.05)	*ns*	*ns*	*ns*

Seed lot	DOUBLE	TARGET	MISS
AMA	29%	51%	20%
CAR217a	34%	45%	21%
CAR219b	33%	45%	21%
Kuroda 1.6-2	36%	41%	22%
Kuroda 2-2.4	33%	48%	19%
Kuroda >2.4	34%	44%	22%
Kuroda <1.6	35%	44%	22%
KADOMA	29%	51%	20%
Kenobi	34%	45%	21%
Mojo	32%	47%	21%
Stefano	36%	42%	22%
LSD p=0.05	*ns*	*ns*	*ns*

Interaction

Bedrow	**Seed lot**	DOUBLE	TARGET	MISS
inner	AMA	38.0%	40.4%	21.7%
inner	CAR217a	34.6%	44.6%	20.7%
inner	CAR219b	35.4%	42.8%	21.9%
inner	Kuroda 1.6-2	33.9%	44.3%	21.9%
inner	Kuroda 2-2.4	32.0%	48.7%	19.3%
inner	Kuroda >2.4	30.6%	46.7%	22.8%
inner	Kuroda <1.6	32.4%	46.7%	20.9%
inner	KADOMA	27.6%	51.9%	20.6%
inner	Kenobi	34.8%	42.6%	22.6%
inner	Mojo	33.7%	45.2%	21.1%
inner	Stefano	35.6%	42.0%	22.4%
outer	AMA	15.0%	66.8%	18.2%
outer	CAR217	33.9%	45.4%	20.7%
outer	CAR219	31.1%	48.1%	20.7%
outer	Kuroda 1.6-2	39.1%	38.1%	22.8%
outer	Kuroda 2-2.4	34.1%	46.3%	19.6%
outer	Kuroda >2.4	36.9%	41.3%	21.9%
outer	Kuroda <1.6	36.7%	40.9%	22.4%
outer	KADOMA	30.9%	50.0%	19.1%
outer	Kenobi	32.6%	48.1%	19.3%
outer	Mojo	30.6%	48.5%	20.9%
outer	Stefano	36.5%	41.7%	21.9%
	LSD p=0.05	*6.0%*	*7.2%*	*ns*

In Trial 3, two precision seed planters, a Stanhay and Accord, were compared in a factorial design consisting of the two planters by 3 target spacings (35, 40 and 50mm). The relationship between the mean spacing achieved and the target spacing is presented in Figure 37. A large variability in spacing was obtained from both planters making it impossible to determine differences in performance between the two. In addition to this the target spacings in this trial were not achieved making it impractical to gauge the effect of spacing (35, 40 & 45mm) on Spacing Index and subsequent carrot quality. An example of the frequency distribution for the intra row spacing is shown in Figure 38 to demonstrate the large variance.



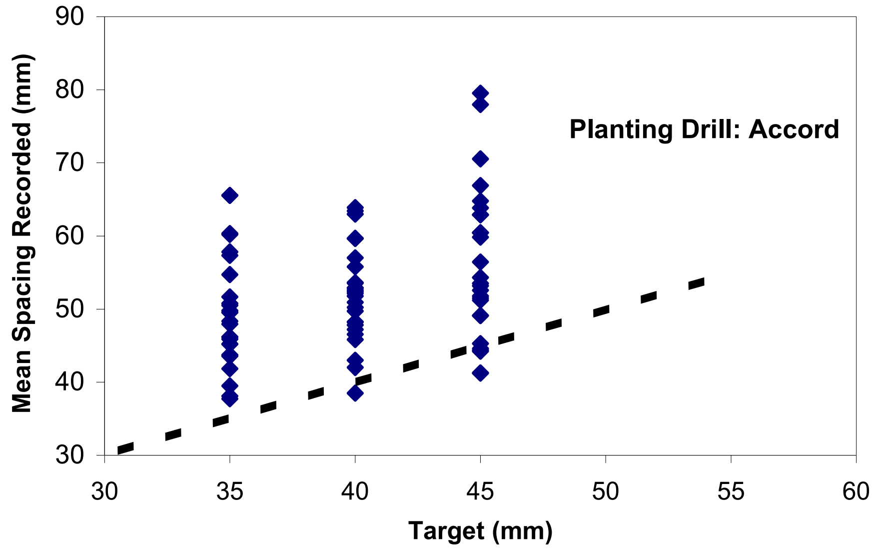


Figure 37. Relationship between target spacing and the mean spacing recorded for (a) Stanhay and (b) Accord precision planters. Each point is mean of 30 readings.

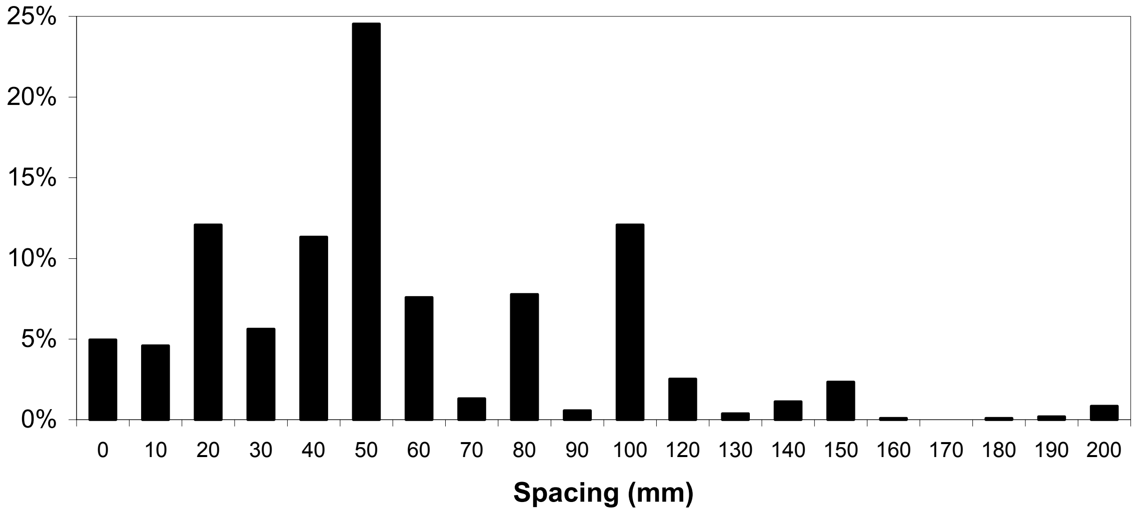


Figure 38. Frequency distribution of the intra row distance between adjacent carrot seedlings planted using Stanhay planter. This spacing distribution was typical for seedlings established with Accord and Stanhay planters.

Yield and Quality

Due the large size of the trials undertaken in this study replicate plots were pooled when grading the carrots. Consequently, the pooling of the samples makes it impossible to statistically analyse differences in responses recorded between carrot varieties planted at a single harvest date. Given that all the varieties trialled were either var. Nantes or var. Kuroda, the pooling of the data for each of the cultivars highlighted some major differences between the two types. The most prominent outcome from this assessment was the high incidence of growth splitting for var. Kuroda compared with var. Nantes (Figure 39). For both cultivars growth splitting only occurred over the final stage of crop maturation, after day 96, however approximately 10% were affected by day 127 for var. Kuroda compared with 1% for var. Nantes (Figure 39).

Statistical analysis of the data collected in Trial 3 (planted on the 22 January 2003) considered the effects of plant target spacing, cultivar and harvesting date on carrot size and quality. The trial was initially analysed as a split plot design. Main plots were harvest dates and subplots consisted of the treatments, planting density and cultivar, in a 3 x 2 factorial. Planting density did not have a significant effect on most responses recorded. This outcome was most likely due to the difficultly in attaining the target spacings as well as the low range of densities examined (35 to 55mm intra row planting spacings). For responses where plant density did not have a significant effect, this source of variance was omitted and in further analyses the densities were deemed replicates, thus providing three replicates for both varieties Stefano and Mojo by 5 harvest dates.

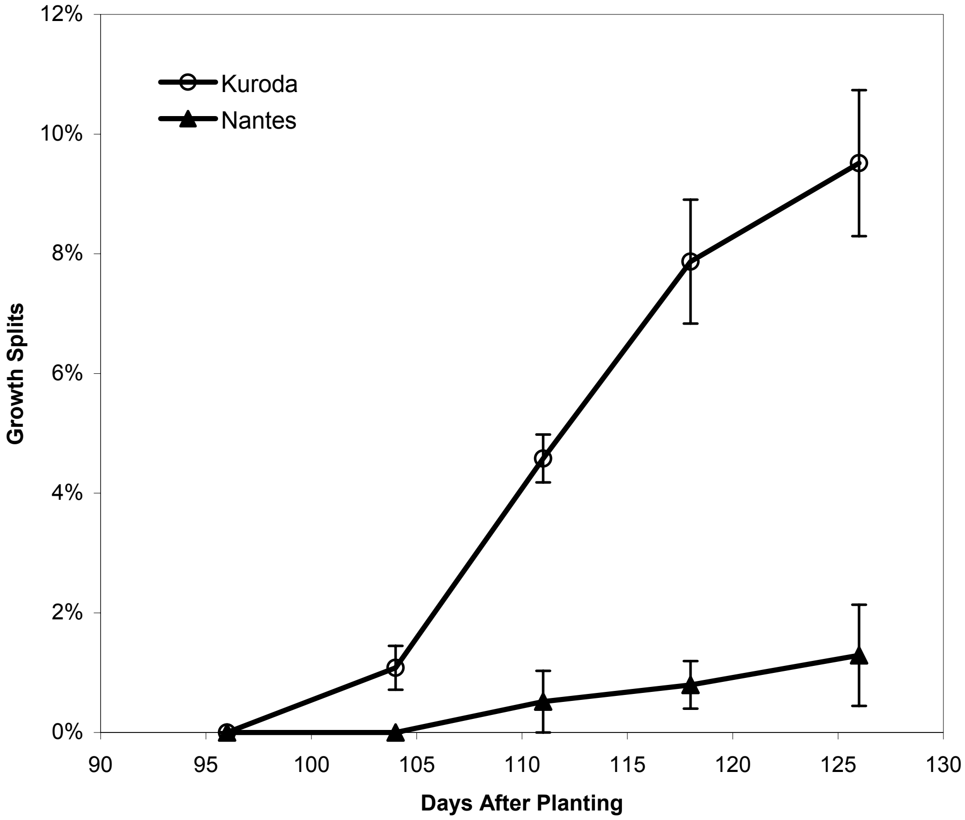


Figure 39. Change in proportion of carrots with growth splits for cv. Kuroda and cv. Nantes. Trial 1

Carrots harvested on each of the five sample dates were sorted into classes of critical faults, non-critical faults and Class 1 quality consistent with commercial guidelines. Class 1 carrots were further graded in to 5 size classes based on shoulder diameter: <25mm, 25-30mm, 30-40mm, 40-45mm and >45mm. Data are presented as percentage on a fresh weight basis.

Of the two Nantes varieties examined in this trial var. Mojo was the higher yielding (*P*<0.01), producing on average 4 to 10 t/ha more than var. Stefano at each harvest date (Figure 40). This outcome demonstrates that var. Mojo has a much higher growth rate than var. Stefano. At the last harvest date (120 DAP) seed sown at 35mm spacing yielded significantly (P<0.01) more than those planted at both 40 and 45mm, independent of variety. Since the highest yields were attained at the highest stand density competition for resources were not a limiting factor in this trial. Furthermore, plants typically display a sigmoidal growth pattern over time. In this trial the exponential component of the S curve, the 'ceiling weight', was not attained indicating the stand density could be increased and/or the crop grown for longer duration to attain even higher yields. However, at higher densities the mean taproot size (diameter, length and weight) declines (Gracie, 2002) and given that mean taproot size is an important marketable trait the impact of longer growing periods and higher densities would need to consider these responses.

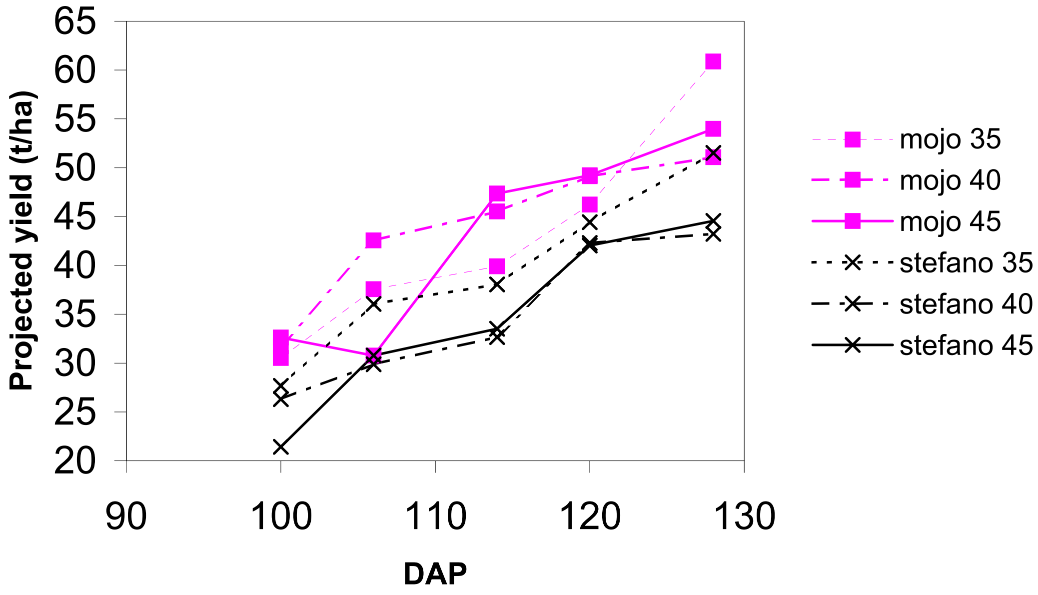


Figure 40. Projected net yields for carrot vars. Mojo and Stefano, planted at 35, 40 and 45mm intra row spacing, harvested on 5 separate dates.

The change in proportion of carrots with non-critical faults with time is shown in Figure 41. The average level of non-critical faults ranged from 12% to 17% for Mojo and 12 to 22% for Stefano over time (Figure 41). A one-way analysis of variance at the last harvest date, 120 DAP, revealed a significantly (*P*<0.05) higher proportion of carrots with non-critical faults for var. Stefano (22%) compared with var. Mojo (12%). It is unclear whether the difference between the varieties at the last harvest date was a random outcome or if there was some underlying cause. A break down of the faults revealed that approximately 80% of the carrots with non-critical faults were misshapen (Figure 42). The significant difference in the proportion of carrots with non-critical faults between the two varieties was due to an increase in misshapen carrots for var. Stefano and a concomitant decrease for var. Mojo.

The critical and other non-critical faults recorded are presented in Table 8. The proportion of carrots with minor faults due to cracks (0.1%), corky crown rot (0.23%), nodules (0.93%), breakage (0.17%) and shoulder discolouration (0.17%) was low and when combined only effected 1.60% of the carrots harvested. Furthermore, time of harvest (DAP), cultivar and spacing had no significant (P<0.05) effect on their incidence in this trial.

A significant difference (*P*<0.05) in the level of forking was detected between the two Nantes varieties. Var. Mojo (1.4%) had a significantly higher incidence of forking than var. Stefano (0.6%). This result may be due to the greater length of var. Mojo taproot and therefore greater exposure to fork causing biota/abiota. The higher level of forking of longer taproots is consistent with findings reported by Gracie (2002).

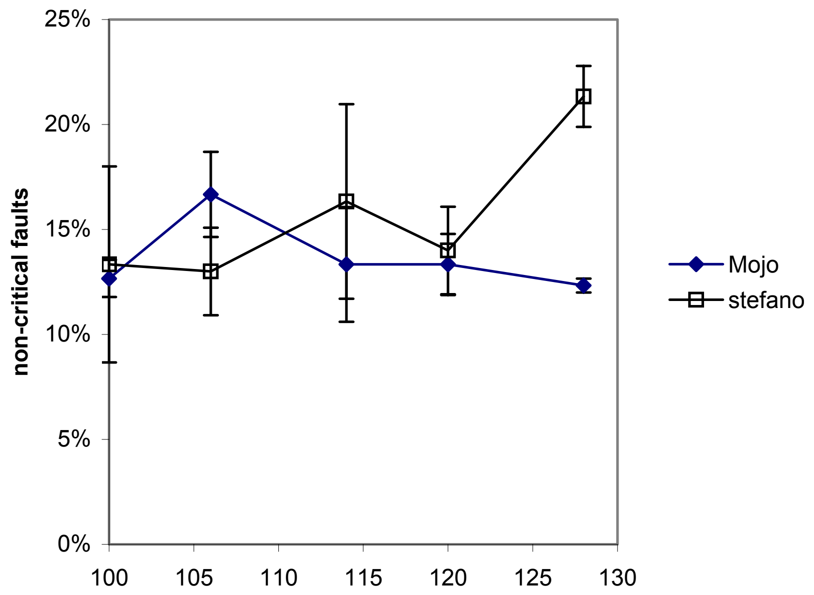


Figure 41. Percentage of carrots with non-critical faults recorded for Nantes varieties Mojo and Stefano. Each point is a mean of 3 replicates. Bars represent SEM.

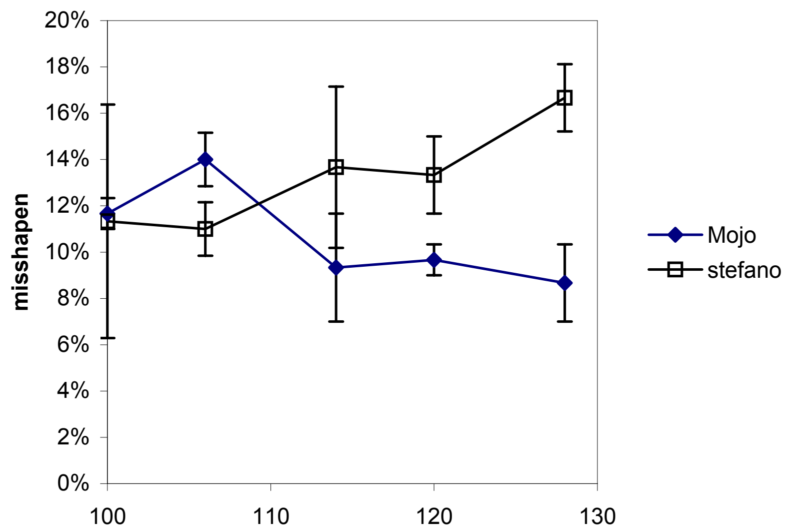


Figure 42. Percentage misshapen carrots recorded for vars. Mojo and Stefano. Each point is a mean of 3 values. Bars represent SEM.

In addition to the grading for critical and non-critical faults, Class 1 carrots were sorted into size classes based on shoulder diameter. In general, the management of carrot size has largely been achieved by manipulating plant density, spatial arrangement and time of harvest (Salter et al., 1979, Salter et al., 1980; Salter et al., 1981). For the Nantes varieties examined in this project, taproots with shoulder diameters between 30-40mm were regarded as optimal. The greatest proportion of carrots falling within this category occurred approximately 120 DAP for both varieties (Figure 43 & 44) regardless of the target density. No significant difference ($P<0.05$) in the maximum percent falling within this category occurred between the two Nantes varieties. The maximum values were extrapolated from the second order polynomial regressions and the averages across the three planting densities were 84% and 83% for Mojo and Stefano respectively.

Table 8. Proportion of carrots with critical faults and non critical faults; cracks , corky crown rot, nodules, breakage, and shoulder discolouration. Data shown for vars. Mojo and Stefano grown at 3 target spacings and harvested on five separate dates.

		Critical faults	
Spacing	DAP	Mojo	Stefano
35	100	0%	0%
35	106	0%	0%
35	114	0%	0%
35	120	0%	0%
35	128	0%	0%
40	100	3%	0%
40	106	2%	0%
40	114	2%	0%
40	120	0%	0%
40	128	0%	0%
45	100	0%	0%
45	106	0%	1%
45	114	0%	0%
45	120	0%	0%
45	128	0%	0%

		Corky Crown Rot	
Spacing	DAP	Mojo	Stefano
35	100	0%	1%
35	106	0%	0%
35	114	1%	2%
35	120	1%	0%
35	128	0%	0%
40	100	0%	0%
40	106	0%	0%
40	114	1%	0%
40	120	0%	0%
40	128	0%	0%
45	100	0%	0%
45	106	0%	0%
45	114	0%	0%
45	120	1%	0%
45	128	0%	0%

		Cracks	
Spacing	DAP	Mojo	Stefano
35	100	0%	0%
35	106	0%	0%
35	114	2%	0%
35	120	0%	0%
35	128	0%	0%
40	100	0%	0%
40	106	0%	0%
40	114	0%	0%
40	120	0%	0%
40	128	0%	0%
45	100	0%	0%
45	106	0%	0%
45	114	1%	0%
45	120	0%	0%
45	128	0%	0%

		Broken	
Spacing	DAP	Mojo	Stefano
35	100	0%	0%
35	106	0%	0%
35	114	0%	0%
35	120	1%	0%
35	128	0%	2%
40	100	0%	0%
40	106	0%	0%
40	114	0%	0%
40	120	0%	0%
40	128	0%	2%
45	100	0%	0%
45	106	0%	0%
45	114	0%	0%
45	120	0%	0%
45	128	0.00	0.00

		Forked	
Spacing	DAP	Mojo	Stefano
35	100	0%	0%
35	106	0%	0%
35	114	0%	0%
35	120	2%	0%
35	128	2%	1%
40	100	2%	0%
40	106	1%	0%
40	114	2%	0%
40	120	1%	0%
40	128	5%	0%
45	100	0%	2%
45	106	0%	2%
45	114	2%	4%
45	120	0%	0%
45	128	5%	0%

		Discolored Shoulders	
Spacing	DAP	Mojo	Stefano
35	100	0%	0%
35	106	0%	0%
35	114	0%	2%
35	120	0%	0%
35	128	0%	3%
40	100	0%	0%
40	106	0%	0%
40	114	0%	0%
40	120	0%	0%
40	128	0%	0%
45	100	0%	0%
45	106	0%	0%
45	114	0%	0%
45	120	0%	0%
45	128	0%	0%

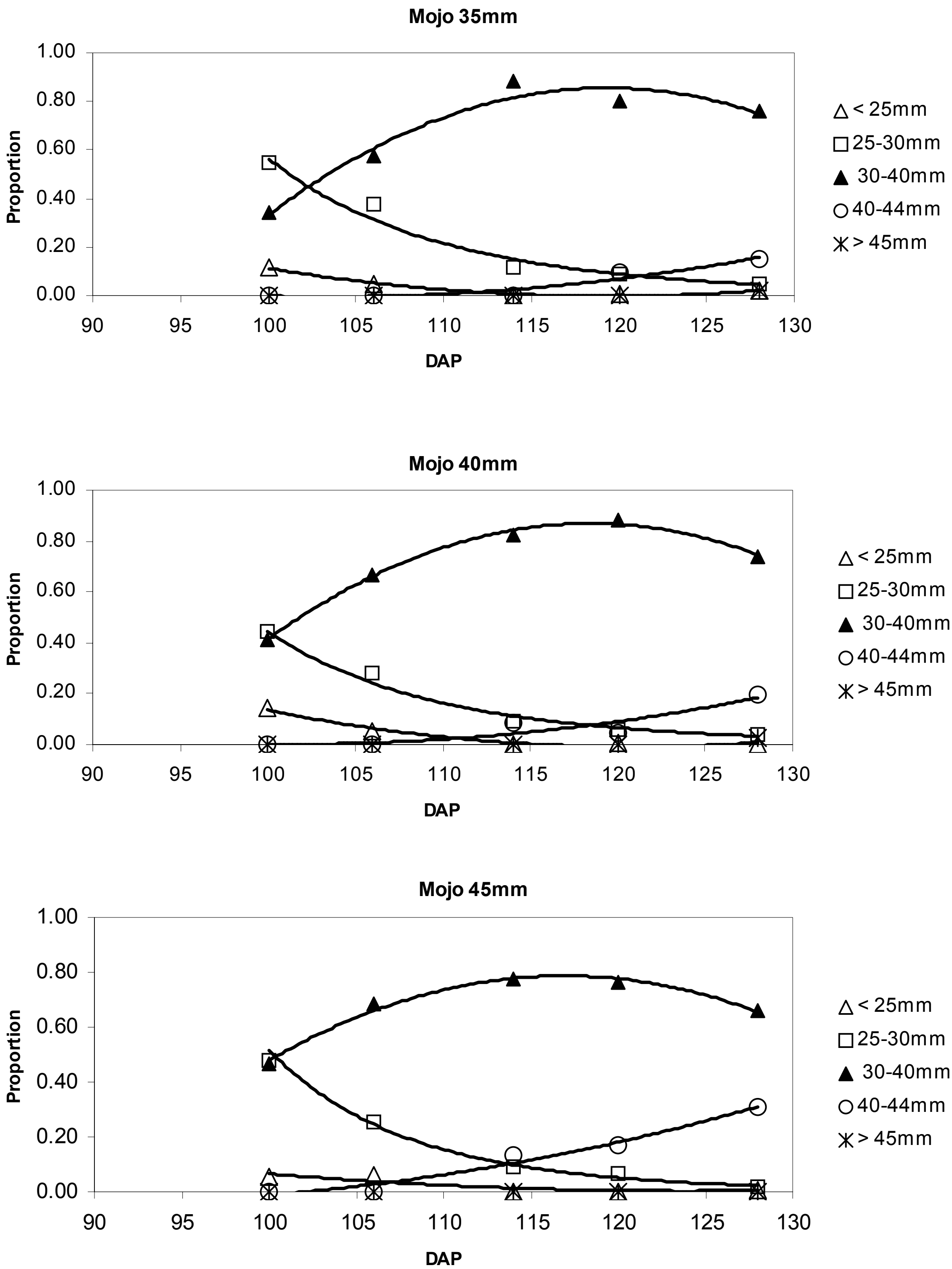


Figure 43. The proportion of carrots falling within size grading; <25mm, 25-30mm, 30-40mm, 40-45mm and >45mm, for var. Mojo harvested on five separate days after planting (DAP). Three target spacings; (a) 35mm, (b) 40mm and (c) 45mm were examined. Regressions are 2nd order polynomials.

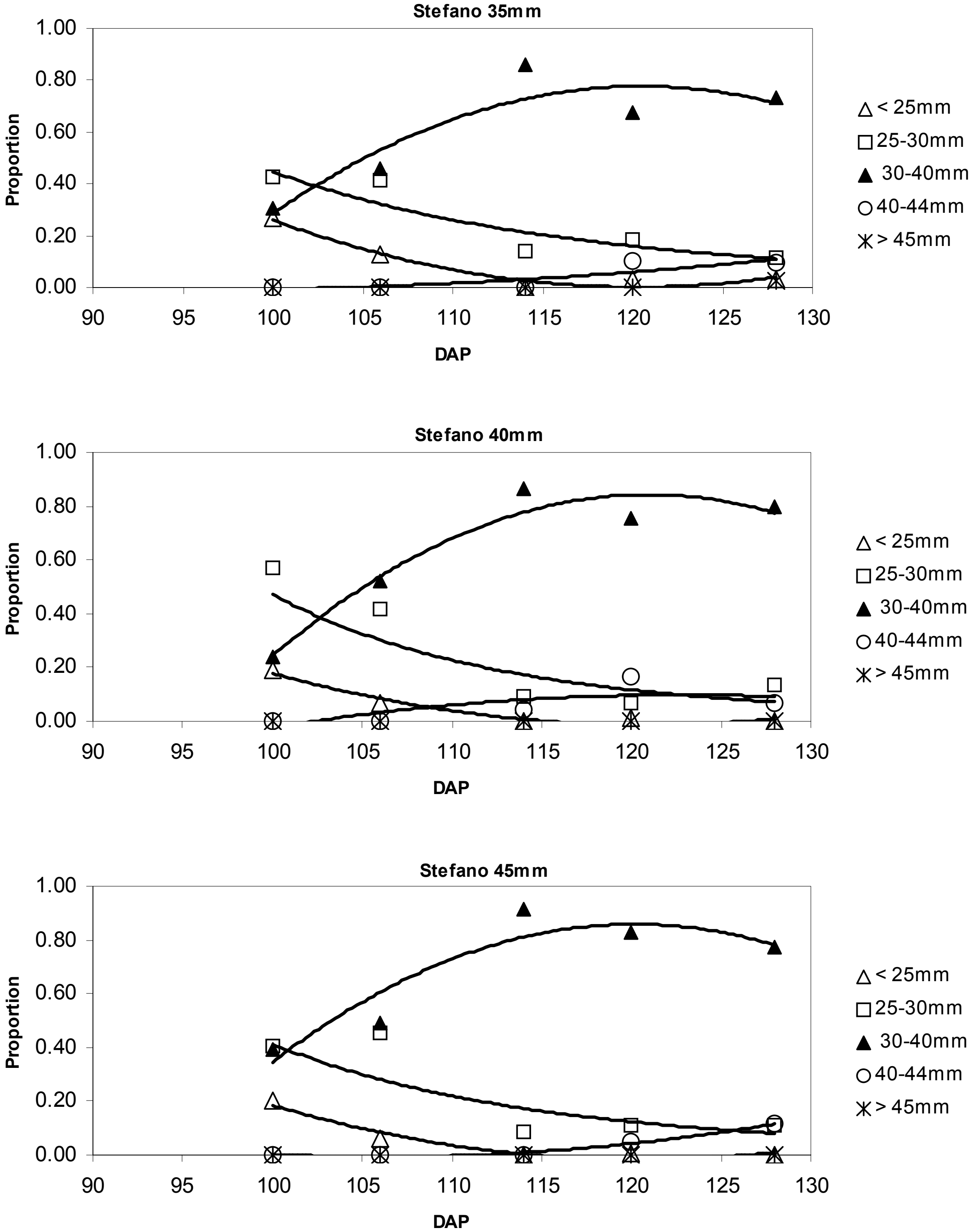


Figure 44. The percentage of carrots falling within size gradings <25mm, 25-30mm, 30-40mm, 40-45mm and >45mm for var. Stefano harvested on five separate days after planting (DAP). Three target spacings; (a) 35mm, (b) 40mm and (c) 45mm were examined. Regressions are 2nd order polynomials.

Rounding of the taproot tip is widely viewed as a measure of taproot maturity (e.g., Howarth et al., 1992). As carrots mature the root tip changes from having a tapered or pointed shape to becoming more rounded (Thompson, 1969; Rosenfeld et al., 1998). In this study, Class 1 taproots were visually classified as tapered, rounded or domed based a photographic key described later (Page 86). This assessment was used as an objective measure of taproot maturity. The increase in proportion of roots classified as domed with later harvests in most of the size classes (Figure 45 and 46) concurs with these reports.

Between 70 - 85% of all carrots harvested over the last three harvest dates (114, 120, and 128 DAP) fell within the size grading 30-40mm (Figures 43 & 44). Within this size grading no significant difference (P>0.05) in the proportion of tapered, rounded and domed taproots between the Nantes varieties Mojo and Stefano was recorded over the last three sample dates, as the carrots approached harvest maturity. However, within this size grading (30-40mm) a significantly higher proportion of var. Stefano carrots had tapered roots compared with var. Mojo carrots 100 DAP suggesting that the var. Mojo either has a higher developmental rate or a greater tendency towards rounding at early stages of development.

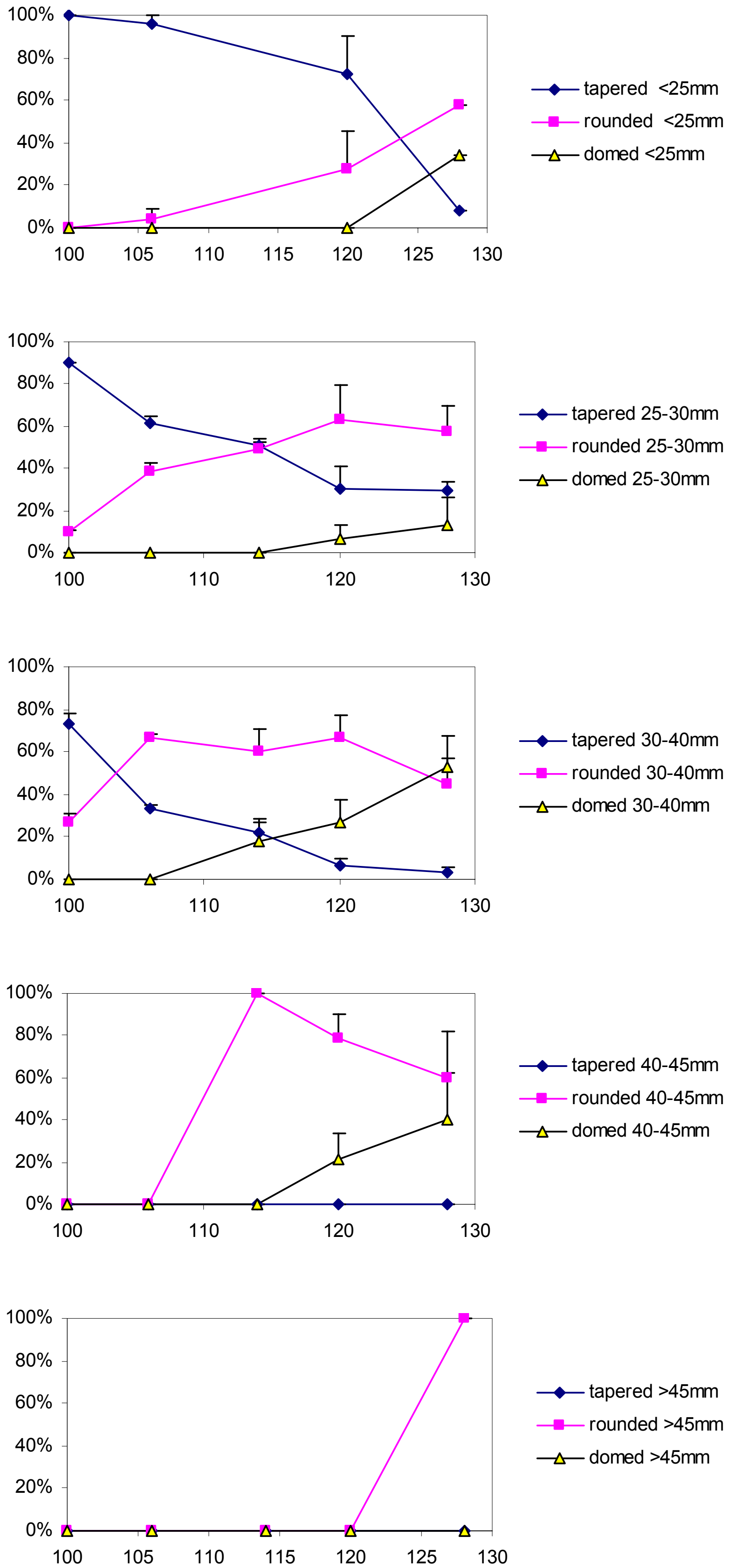


Figure 45. Proportion of carrot taproots (var. Stefano) with tapered, rounded and domed tips in five diameter size ranges: (a) <25mm, (b) 25-30, (c) 30-40, (d) 40-45, and (e) >45mm. Carrots were harvested 100, 106, 114, 120 and 128 DAP. Each point is a mean of 3 replicates and bars represent 1 SEM.

Mojo

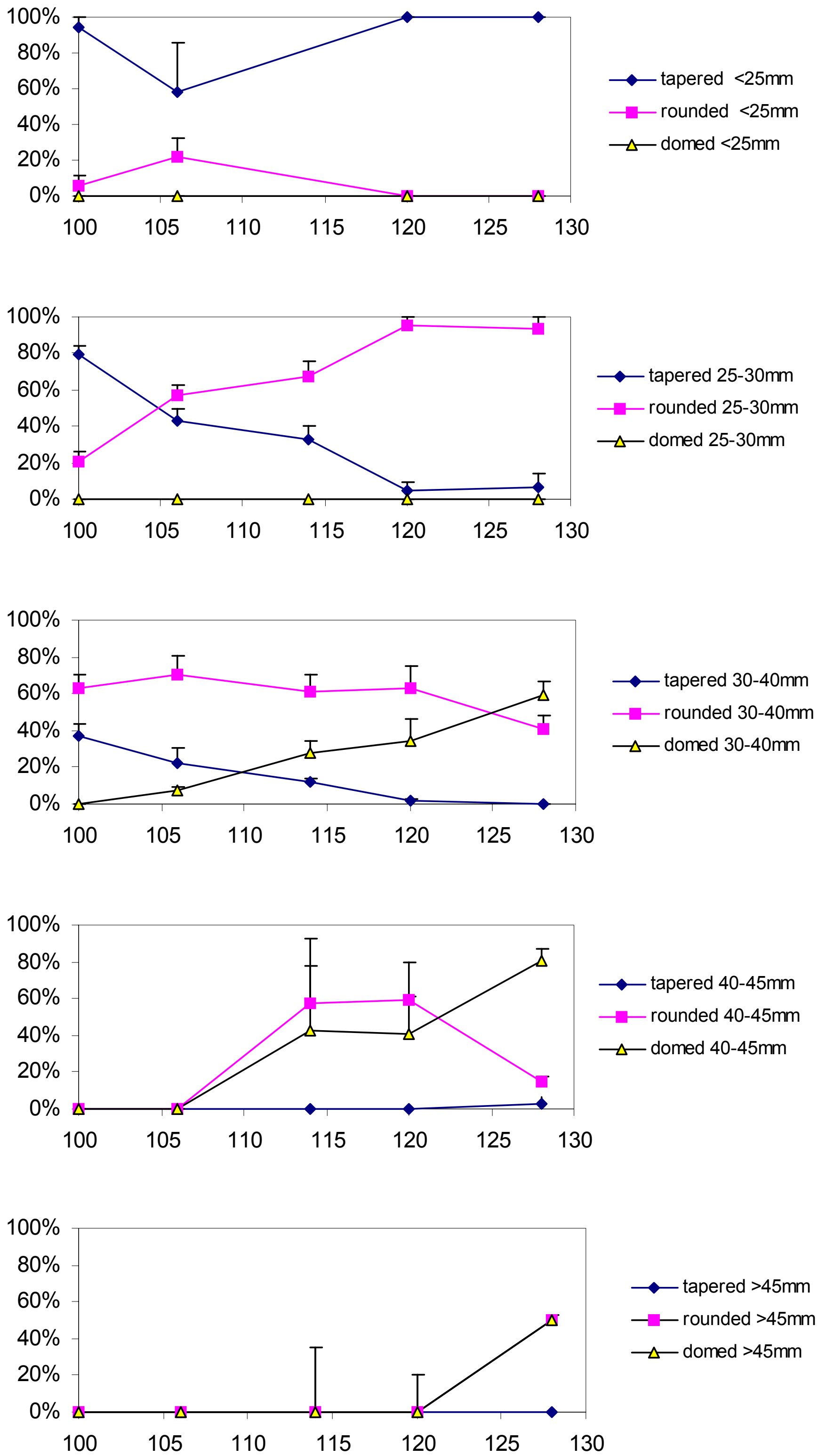


Figure 46. Proportion of carrot taproots (variety: Mojo) with tapered, rounded and domed tips in five diameter size ranges: (a) <25mm, (b) 25-30, (c) 30-40, (d) 40-45, and (e) >45mm. Carrot were harvested 100, 106, 114, 120 and 128 DAP. Each point is a mean of 3 replicates and bars represent 1 SEM.

Improving the crop harvest index for Fresh Market Kuroda carrots

Measuring tip rounding as an index of harvest maturity

The carrot harvest index is intended to provide an indication of a crop's maturity in relation to the desired market requirements. It does not represent physiological maturity. Consequently both Kuroda and Stefano carrots are often still actively growing when carrot crops are harvested for the fresh market.

The marketing of carrots places the greatest emphasis (with the exception of defects and disease) on carrot size. For this reason it' s likely that the proportion of carrots across size classes would, for most packers, be the principle parameter driving a harvest index. Tip rounding from a marketing perspective, while important, is secondary to taproot shoulder diameter.

Carrot root tip shape is influenced by cultivar, environmental conditions and developmental stage (Rubatzky 1999). As many carrots will not have reached physiological maturity at the time of harvest, it is possible that many carrots will not have begun rounding off when the required shoulder diameter size class proportions have been reached.

Methodology

In a series of experiments, samples of 10 carrots were hand harvested from commercial crops at various stages of crop maturity and used to evaluate the effectiveness of a range of methodologies for assessing root tip shape. For each carrot, shoulder diameter and diameters at 10mm, 20 mm and 40 mm from the taproot tip were recorded in addition to taproot weight and length. Carrot tips were defined as starting at the point at which the root was 2mm in diameter. After measuring shoulder diameter, length and weight, the taproots were progressively severed 40mm, 20mm and 10mm from the tip. Each severed section was pierced with a stretched paper clip attached to string and lowered into a measuring cylinder containing a known amount of water. The volume of displaced water was taken to be the volume of the carrot tip. The actual tip volume measured (TVa) was then compared with the theoretical tip volume (TVt) of a cylinder, cone and dome, based on the diameter of the sectioned tissue as measured prior to severance. Carrots with a TVa/TVt ratio of 1.0 were hypothesised to have a tip conforming to the ideal geometric shape being compared.

Results and Discussion

Regardless of the geometrical shape (cylinder, cone or dome) used to derive the theoretical tip volume (TVt) this procedure was not sensitive to subtle or sometimes even gross changes in tip shape. As the trials progressed it became obvious that a visual assessment of carrot tip shape was likely to be more effective, practical and efficient, particularly if it was to be incorporated into a commercial pre-harvest procedure.

Development of a photographic key

To provide a rapid visual assessment of tip rounding, a photographic key was developed (Appendix 3), illustrating three broad categories of tip rounding. These categories were:

1. Tapered carrots – the carrot tip tapers to a fine point with no signs of tip fill.
2. Rounding carrots – the carrot tip is no longer tapered, is rounding off, but has not reached the classic Kuroda tip shape.
3. Domed – the carrot has reached its classic domed tip shape associated with harvest maturity.

Although subjective, this method provides for a rapid visual assessment of carrot tip shape offering an extra tool in the assessment of a crop's readiness for harvest.

1.8 1.7 1.6 1.5 1.4 1.9 1.3 2.3 2.4. 1.1

Figure 47. Example of carrots used in study of carrot tip Tva/TVt ratios for cylindricality. White numbers marked on the taproot identify the replicate, numbers below the carrots are the TVa/TVt ratio at 10mm from the tip.

Carrot #	Length (mm)	Diameter @ 10mm	Actual Tip Volume (TVa)	Shoulder Width (mm)	Theoretical Tip Volume (TVt)	TVa / TVt
1	205	29	4	49	*2.2*	1.8
2	143	21	2	41	1.2	1.7
3	187	22	2	56	1.3	1.6
4	166	16	1	43	0.7	1.5
5	166	23	2	53	1.4	1.4
6	156	14	1	39	0.5	1.9
7	162	12	0.5	37	0.4	1.3
8	156	13	1	38	0.4	2.3
9	108	25	4	47	1.6	2.4
10	179	13	0.5	32	0.4	1.1

Table 9. Example of typical results derived in a comparison of actual vs. theoretical tip volumes for cylindricality. Carrots used in this study are illustrated in Figure 47.

Technology Transfer

Due to the unique nature of the relationship between packers and contracted growers in Tasmania, growers taking advice from company agronomists have directly adopted findings from this project. The findings from this study were presented to growers at Field Fresh Tasmania grower meetings and have been included in crop specification documents circulated at these meetings. Field Fresh Tasmania has also adopted a number of key findings into its commercial crop production program:

These include:

- The use of a penetrometer to assess crop splitting propensity prior to the beginning of harvest each morning, when the risk of splitting is considered likely.
- Modified agronomic advice regarding irrigation prior to harvest. The modified irrigation program resulted in a reduction in carrot splitting across the season.
- The inclusion of a visual assessment of carrot root tip rounding in the pre-harvest assessment protocol.
- Crop planting configurations modelled on the findings of this project.
- An increased effort to maximise the accuracy of intra row seed placement.
- The use of graded carrot seed.

These changes have directly increased gross yield, net yield (pack out) and improved returns to growers.

Discussion and Recommendations

Technologies to abate carrot splitting and physical damage

Carrot splitting, shape aberrations and large size variation have been identified by industry representatives as the major causes of reduced marketable yield of fresh carrots cultivated in Tasmania. An increase in the proportion of Class 1 grade carrots would substantially improve production efficiencies, enable carrot export companies to maintain a ready supply of premium grade carrots to markets that demand such standards and provide greater fiscal returns to local growers. Innovative commercial strategies to reduce the level of losses based on recent research were examined in this study.

The carrot splitting disorder affects approximately 6% of all fresh carrots cultivated in Tasmania for premium export markets. Previous research undertaken by researchers at the University of Tasmania demonstrated the major impetus for splitting to be rapid growth of the inner phloem tissue, as a result of high turgor and/or cell wall synthesis (Gracie, 2002). Gracie and Brown (2002) proposed strategic application of leaf trimming to mature carrots as a possible technique for reducing tissue growth in the inner phloem zone, and in turn reduce splitting susceptibility. This work formed the basis of leaf trimming trials investigated in this study. The leaf trimming trials included time of trimming, quantity of foliage removed, and duration between leaf trimming and harvesting.

In general, the greater the quantity of foliage removed the greater the reduction in splitting susceptibility. In one trial, vertical and horizontal trimming reduced splitting for a 10-day period while complete defoliation reduced splitting for a 12-day period. The trial in question was well irrigated and the soil moisture maintained at a high level in accordance with commercial recommendations. However, the results from other leaf trimming experiments were variable and defoliation did not always result in reduced splitting propensity. The reason for the lack of treatment response under some conditions is unclear. From observation it appears that the higher the splitting susceptibility and the higher the soil moisture content is maintained the more likely a response to leaf trimming will be recorded. The size of the canopies being treated, and thus the amount of foliage removed, varied across crops and represent another parameter that was largely uncontrolled. The time of day leaf trimming is applied did not have a significant effect on the response to splitting in this study.

Based on some promising results showing that leaf trimming can effectively reduce carrot splitting under certain circumstances, mechanical leaf trimming equipment was constructed and has been used in commercial crops. The equipment applied both horizontal and vertical trimming and removed a significant quantity of foliage yet left sufficient petiole material to permit mechanical harvesting by top lifting. However, the response to splitting following leaf trimming was variable.

Major findings and recommendations associated with leaf trimming:

- The modified handheld penetrometer provided an ideal tool for rapid measurement of splitting propensity in the field. Construction of a similar tool or refinement of the handheld penetrometer used in this study may be of benefit to producers to identify crop's susceptible to splitting prior to the commencement of harvest.
- Growth splitting occurred mainly in the later stages of crop development.
- High soil moisture content at harvest exacerbated splitting susceptibility. Allowing the soil to dry slightly before harvesting may lessen splitting.
- Time of day leaf trimming was applied did not affect the splitting response.
- Generally, a greater reduction in splitting is recorded with a higher level of defoliation
- Under conditions where partial defoliation reduced splitting the response lasted for a 10 day period, while compete defoliation reduced splitting for a 12 day period.
- In most cases, the leaf trimming equipment employed removed sufficient foliage yet still permitted mechanical harvesting by top lifting.
- Taproot splitting susceptibility response to leaf trimming was variable and more research is required before this novel strategy can be implemented with repeated success in a commercial setting. The following research is recommended:
    - A greater understanding of the interaction between environmental variable (such as temperature, soil moisture content, and nutrient availability) and splitting is required.
    - A greater understanding of the interaction between environmental variables and response to splitting following leaf trimming is recommended.
    - The relative role of turgor and cell wall growth of the inner phloem tissue in inducing splitting is required to develop a greater understanding of the splitting process. Again with particular reference to prevailing environmental conditions.

As mentioned above, complete defoliation provided the greatest reduction in splitting in one experiment, with the effect lasting for a 12-day period. The trial in question was well irrigated and soil moisture was maintained at a high level for the duration of the experiment. Based on this result an alternative harvesting technique was examined involving complete defoliation followed by shear lifting. A slasher was used to defoliate taproots prior to harvesting. Setting the slasher height to minimise losses associated with scruffy tops (too much leaf material remaining) and taproot physical damage (due to damage from the slasher blades) proved difficult on the undulating topography found on the northwest coast of Tasmania. An alternative device for removing the foliage, such as an infield carrot crowner, is recommended. In addition to the difficulties associated with removing the foliage the alternative harvesting operation of shear lifting caused substantial physical damage to the surface of the taproot. The alternative harvesting operation assessed in this study requires significant improvement to be considered a suitable replacement for the current harvesting technique for high quality fresh carrots.

Given the limited success in reducing splitting associated with partial and complete defoliation an alternative strategy of undercutting carrots was investigated. The strategy was based on previous work by Brown and Gracie (2000) who demonstrated that lifting carrots slightly to detach the fibrous root from the taproot resulted in reduced levels of splitting. The undercutting bar was adjusted to impose different levels of root disturbance and therefore soil water uptake. When the level of disturbance was too low splitting was not reduced and when the level of root disturbance was high splitting was reduced, but severe plant wilting impeded harvesting by top lifting harvesting and adversely affected taproot quality.

Major findings and recommendations associated with alterative treatments and harvesting technique to reduce splitting:

- The use of a slasher was found to be inappropriate for the purpose of defoliation. An infield carrot crowner is recommended for this task.
- Carrot harvesting by shear lifting caused substantial damage to the surface of the taproots and requires significant improvement before it can be deemed a suitable replacement to top lifting.
- Undercutting taproots can be employed to successfully reduce splitting, but requires further refinement to be considered a viable option.
- Too much fibrous root disturbance causes sever wilting and hinders harvesting by top lifting. The wilted taproots also require re-hydration.

Minimising carrot shape defects and size variation

Carrot shape is an important marketing parameter. Misshapen taproots represent approximately one third of all carrots falling below the Class 1 quality and although this disorder is of significant commercial importance it has received very little attention in published literature. A recent study demonstrated that the physical properties of the ferosol soils, on which the carrots are grown on the northwest coast of Tasmania, have some influence on the incidence of misshapenness (Gracie 2002). Furthermore, the same study also reported that the evenness of intra row spacing has a significant impact on the incidence of taproots with shape aberrations (Gracie, 2002). This latter finding formed the basis of much of the research undertaken in this project to reduce misshapenness.

The other major cause of reduced pack out is the large variance in carrot sizes within a crop. Although crops are harvested based on average taproot size a substantial proportion are smaller and larger than the stringent market specifications. Production practices examined to reduce incidence of taproot misshapenness and size variation involved manipulating plant spatial distribution. Trials undertaken included; evenness of intra-row spacing, row configuration, stand density, seed grading and type of precision planters.

Spacing Index analysis revealed that the evenness of intra spacing in commercial carrot crops is well below that recorded for other vegetable crops, with only approximately 50% of all seeds falling within the acceptable target spacing range. Seed lot size grading had only a small impact on the proportion falling in the target range. Similarly, the type of precision drill used, stand density and row arrangement had only negligible impact on the proportion falling within the target spacing range.

Changing the planting configuration on a raised bed from 6 double rows to 4 single rows increased the level of carrots falling with the medium size range and reduced the proportion of misshapen carrots. However, there was a trade-off associated with lower yields due to the lower stand density planted.

A visual key for assessing the degree of rounding of the taproot tip was also developed in this study. This important marketing characteristic has been implemented into the pre-harvest assessment program of a local packing company.

Major findings and recommendations on minimising carrot shape defects and size variation:

- Kuroda carrot types were more susceptible to growth splitting than Nantes types
- The longer Nantes carrots types were generally were more prone to forking, most likely due to greater exposure to 'fork-causing' biota/abiota.
- The development of a protocol for grading carrots according to tip shape was successfully developed.
- Of the two main Nantes types (vars. Mojo and Stefano) examined in this study var. Mojo was faster growing and the root tip rounded earlier.
- Sowing configurations that result in lower stand densities resulted in a lower incidence of misshapen carrots (thus higher proportion of marketable carrots), but a lower gross yield.
- Large variation in intra-row plant spacing currently exists within the commercial system. Increasing the evenness of intra row spacing could reduce both the incidence of misshapen carrots and size variation
- The precision of two widely used vacuum air seeders were compared and did not differ significantly
- Seed size grading had only a small impact on the evenness of spacing
- A major finding from this study was the need for care when analysing spacing Index based on target density when it was not achieved. Basing the Spacing Index calculations on the mean density achieved, as opposed to the target spacing, provided a way of eliminating any bias associated with difference in actual and target density.
- This study highlights the need for commercial strategies for increasing the evenness of intra–row spacing of carrot plants.

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Appendix 1

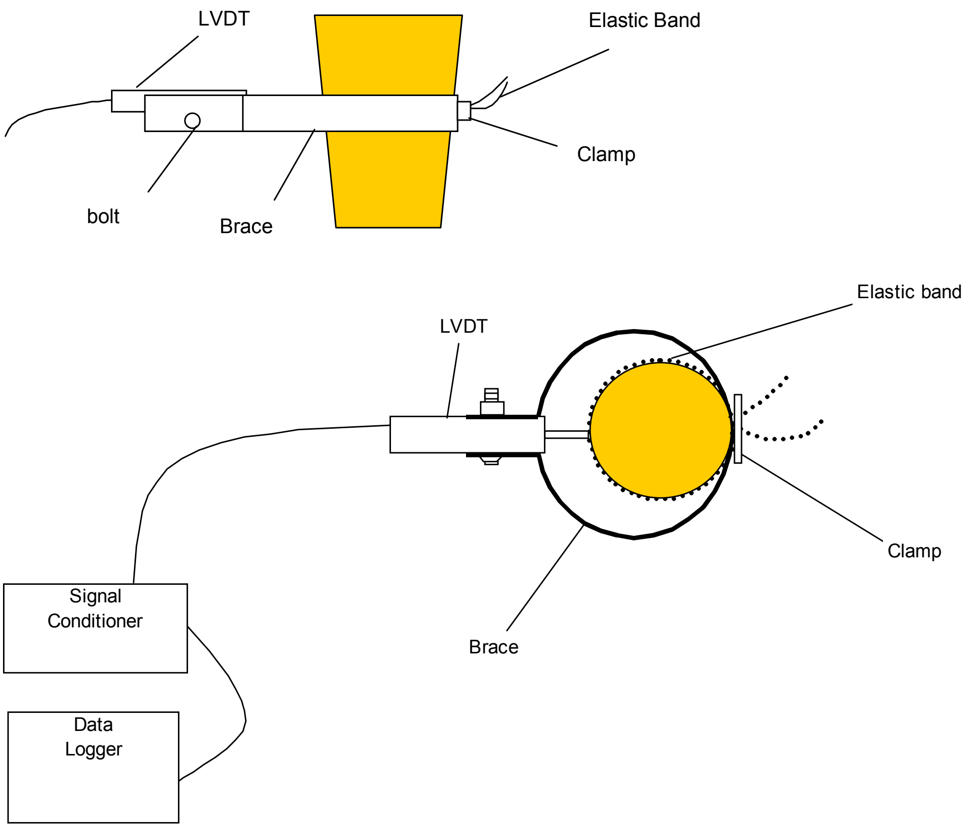
Rainfall data for Cuprona field monitoring site.

Date	Wet Site Rainfall	Wet Site Irrigation	Dry Site Rainfall	Dry Site Irrigation
28/03/2003		7.5		
29/03/2003	9.5		9.5	
30/03/2003				18
31/03/2003		9.5		
2/04/2003	1.5		1.5	
5/04/2003		19.5		
6/04/2003				19.5
7/04/2003		9.5		
8/04/2003	4.75		5	
10/04/2003	0.5		0.5	
12/04/2003	40		40	
14/04/2003	51		49	
15/04/2003	6.5		6.5	

Appendix 2

The change in diameter of carrot taproots was recorded using linear variable displacement transducers LVDT (Solarton model. SM3, ± 3 mm stroke range). The set up used is illustrated below.

Soil was carefully removed from the top 20 mm of each taproot monitored, and the surface of the taproot cleaned using a tissue. A brace, either 60 mm or 70 mm in diameter (depending on the diameter of the taproot) was carefully placed around the petioles then lowered over each taproot and rested on the soil. The back of the brace was held firmly to the surface of the taproot by looping an elastic band around the taproot and through two holes (approximately 1 cm apart) drilled in the back of the brace. The ends of the elastic band were fastened at the back of the brace using a clamp. The elastic band secured the brace to the taproot without restricting expansion of the taproot. The LVDT case was secured horizontally and the LVDT rod was spring loaded onto the surface of the taproot at a point just above the elastic band (Method from Gracie, 2002 with permission).



Diagrammatic representation of the design used to measure change in taproot diameter as viewed from the side (a), and top (b). Not to scale. Sourced from Gracie (2002) with Permission

Appendix 3

Harvest Maturity Index – Tip Shape Assessment

Tapered Carrots

The carrot tip tapers to a finepoint with no signs of tip fill.

Rounding Carrots

The carrot tip is no longer tapered, is rounding off, but has not reached the classic dome shape.

Domed

The carrot tip has reached a classic dome shape.