Improving yield and quality of process carrots through better crop establishment

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Abstract

Increasing the yield and quality of carrots grown for processing is a priority target for growers and processors in New Zealand. Previous research has highlighted that crop establishment is a major factor in obtaining high carrot yields, and anecdotal observations suggest that there are large differences between targeted and actual plant populations and spacing. A crop survey of 14 sites in Canterbury and Hawke's Bay (representing approximately 25% of the total area grown for processing carrots) during 2013-14 season showed that final carrot establishment ranged from 31 to 96% of target populations. This can result in large yield penalties, with predictions using a validated plant model indicating a loss of total yield of up to 38 t/ha. The average across all sites was a loss of 11 t/ha. Poor establishment outcomes were also predicted to have a strong effect on root size, an important processing attribute to maximise packout. Sowing depth is a critical management factor in ensuring favourable conditions for seed germination and that target populations are achieved. However, climatic conditions can interact with sowing depth in influencing these outcomes. Two sowing depth trials in Canterbury and Hawke's Bay were set up to quantify the effect of shallow, normal and deep treatments on establishment and productivity outcomes of process carrots. Shallow sowing (18 mm depth) in Hawke's Bay achieved the highest established population of 145 plants/m^2, compared with the deep treatment (30 mm depth), with 116 plants/m^2. In Canterbury, deep sowing (26 mm depth) established 29 plants/m^2, compared with the shallow treatment (8 mm depth) population of 16 plants/m^2. The target populations at the respective sites were 140 and 41 plants/m^2. At the Hawke's Bay site, the normal treatment (25 mm depth) produced the highest total root yield of 104.3 t/ha, but the shallow treatment produced the highest marketable yield (root diameter <30 mm) of 75.2 t/ha. Yield could not be measured at the Canterbury site.

Additional keywords: *Daucus carota*, emergence, crop survey, sowing depth, crop production

Introduction

Demand for high health carrot products both internationally and domestically is providing an opportunity for the New Zealand juice and processing industry to expand production. However, increased yields of high quality product and more efficient use of agri-inputs over and above current practices are needed. Poor or variable carrot establishment can have a major impact on final yield and quality (Finch-Savage, 1988; Schoneveld, 1990). Generally this can be accounted for by three main factors: 1) planting equipment not sowing the correct populations; 2) poor germination, because of a mix of biotic and abiotic factors; and 3) failure after germination, because of a mix of biotic and abiotic factors. Carrot seedlings are difficult to establish when seedbed and environmental conditions are not favourable, as their emergence vigour is very low compared with those of other species (Tamet *et al.*, 1996). Unfavourable conditions not only affect emergence times and rates, but also subsequent seedling growth and establishment (Tamet *et al*., 1996). Previous studies have suggested that field emergence can range from 30 to 90% of target populations (Schoneveld, 1990), which can affect marketable yield significantly. There is little recent New Zealand specific published information on typical establishment outcomes for process carrots, or on the effects of key establishment decisions on yield and quality.

This paper reports on a crop survey in the 2013-14 production season that looked at carrot establishment variability across 14 commercial sites located in Canterbury and Hawke's Bay, New Zealand. Two sowing depth experiments (Canterbury and Hawke's Bay) were subsequently conducted during the 2015-16 season to quantify the effects of seed sowing depth on carrot establishment and productivity outcomes.

Materials and Methods

Crop survey

A survey of commercial process carrot fields in Canterbury and Hawke's Bay was conducted during the 2013-14 production season to collect baseline data on establishment outcomes covering a wide range of conditions. The data were then used in a validated plant model to test the effect of targeted and measured plant populations on predicted yield and root size outcomes.

Commercial process carrot fields in Canterbury (10 sites) and Hawke's Bay (four sites) were identified by industry representatives. At each site, four permanently placed plots were established post sowing, but before emergence. The plots were randomly located across each site to capture a range of potential within-field establishment outcomes. Each plot was 1 m long x 1 bed wide (1.8 m and 2.0 m for Canterbury and Hawke's Bay, respectively). Bed configurations (number of rows and related row and plant spacing) differed among sites depending on grower practice and the targeted end-use of each crop (juice, rings, dice or baby carrot products). All sites were managed by growers in association with processing company agronomists. The carrot cultivars grown differed according to end-use and among sites ('Carson', 'Chameray', 'Kamaran', 'Namdal', 'Sprint' or 'Bastia'), as did sowing population, which ranged from 0.5 to 1.4 million seeds/ha. Sowing dates ranged from 2 October to 11 December 2013.

Emergence was monitored every 1–2 weeks until the population stopped increasing. Four to six counts were taken over the monitoring periods at each site. Emergence was defined as any visible sign of the plant above the soil surface.

The Carrot Calculator (Reid, 2005) was used to examine the effect of plant population on potential yield and predicted yield outcomes. Key input variables for each field included: cultivar, target plant populations (specified by the grower) and measured plant populations. Soil fertility and water supply were not limited within the simulations. Weather data (air temperature, rainfall and solar radiation) were derived from the virtual NIWA network, and irrigation dates and amounts were supplied by the growers. Key output variables for each field included fresh yields and mean root size.

Sowing depth experiments

Two field experiments were conducted during the 2015-16 production season to test the effects of different sowing depths on establishment outcomes and yield of process carrot crops. One of the sites was located in Barrhill, Canterbury (43° 39' S, 171° 49' E), and the other in Paki Paki, Hawke's Bay (39° 42' S, 176° 48' E). Three sowing depth treatments (shallow, normal and deep) were selected. The collaborating growers identified their standard practices according to the soil conditions at the time of sowing. Shallow and deep sowing depth was varied around the normal sowing depth (grower standard practise) by raising or lowering the individual coulters on the drill. Both trials were set up as randomised block designs, with individual plots measuring 10 m long x 1 bed (1.8 m and 2.0 m for the Canterbury and Hawke's Bay sites respectively) wide, replicated seven and six times at the Canterbury and Hawke's Bay sites respectively.

The soil type at the Canterbury site was a Barrhill deep fine sandy loam with good drainage. The site was previously in perennial ryegrass for 18 months and was ploughed on 10 October 2015. Barley seed (60 kg/ha) was broadcasted prior to power-harrowing (single pass). The barley was sown to help protect carrot seedlings from wind damage during emergence. Pelleted carrot seed ('Carson', germination rating 89%) was sown on 3 November 2015 with an Agricola air seeder (eight rows/bed) on the flat. Within-row seed spacing was 96 mm, with a target sowing rate of 463,000 seeds/ha. The site was irrigated (gun irrigator), although the first application did not occur until 13 January 2016.

The soil type at the Hawke's Bay site was a Paki Paki loam over sandy loam. The previous crop was annual ryegrass, which was sprayed out and cultivated by discing and power-harrowing. Raised beds were then formed. Pelleted carrot seed ('Nandal', germination rating 85%) was sown on 8 November 2015 with an Agricola air seeder (12 rows/bed). Within-row seed spacing was 36 mm, with a target sowing rate of 1.4 million seeds/ha. The site was irrigated (linear irrigator), with the first application occurring one day post planting. Carrots grown at both sites had different end-uses, of dicing and ring carrots for the Canterbury and Hawke's Bay sites respectively.

Actual sowing depths were measured in each plot by carefully clearing the soil within a row, until the top of a carrot seed was exposed. Sowing depth was then determined by measuring the distance between the top of the exposed carrot seed and the final soil seedbed level 12 times per plot at the Canterbury site and eight times per plot at the Hawke's Bay site. Average sowing depths for the shallow, normal and deep treatments respectively were 8, 16 and 26 mm for Canterbury and 18, 25 and 30 mm for Hawke's Bay.

Carrot emergence was monitored 1–3 times per week by counting the number of emerged plants in each plot until the population had stopped increasing over three successive counts. Totals of 16 and seven counts were taken over the monitoring period at the Canterbury and Hawke's Bay sites respectively. Emergence was defined as any visible sign of the plant above the soil surface and was tracked within a permanent 1 m long x 1 bed wide quadrat in each plot.

Within-row plant spacing was measured within the permanent quadrat once the population had stopped increasing. A 1-m ruler was laid down alongside each individual row and the distance of plants along the row was recorded. This was then used to calculate the within-row spacing between plants. Spacing was then classified using the method of Kachman and Smith (1995) where doubles were <0.5 times the target spacing, singles were 0.5-1.5 times the target spacing, and misses were >1.5 times the target spacing. Gaps >2.5 times the target spacing counted as two misses.

Final yield and root quality were assessed at the Hawke's Bay site from the 1 m x 1 bed plot used to monitor emergence. Sampling was timed to coincide with the commercial harvest. Carrots were lifted and counted, and then separated into leaf and root components. Fresh mass was recorded and then sub-samples of leaf (approximately 250 g) and five roots were oven dried at 60°C until constant mass. Leaf area was also measured using a leaf area meter prior to oven drying. A separate sub-sample of 50 carrots was also used to measure individual root length, diameter and mass. No reliable harvest measurements could be taken at the Canterbury site because of field factors that compromised the crop.

Climate data for the sowing depth experiments were sourced from NIWA weather stations nearest the two trial sites (Winchmore EWS for the Canterbury site and Whakatu EWS and Te Aute Rd for the Hawke's Bay site). Key weather data collated for the trial periods included: daily mean air temperature, rainfall and solar radiation. Growing degree days (GDD) were calculated for both sites using a base temperature of 0.4°C (Reid, 2005). Rainfall at the Canterbury site for the month of November (starting 3 November 2015), December and January was 14.4, 16.0 and 141.2 mm respectively, with the 10-year long-term average being 43.3, 77.4 and 51.7 mm respectively. Rainfall for the Hawke's Bay site for the month of November (starting 8 November 2015), December and January was 38.2, 25.0 and 52.7 mm respectively, with the 10-year long-term average being 29.0, 56.2 and 58.4 mm respectively. The Canterbury site received a total of 230 mm of irrigation throughout the growing season starting on 13 January 2016, compared with that at the Hawke's Bay site, with a total of 450 mm starting on 9 November 2015. Soil temperatures and volumetric water content (VWC) at 20 mm depth were measured at both sites using Decagon soil moisture and temperature probes. An estimate of relative plant available water content (ERPAWC; expressed as a percentage of observed upper and lower observations) was subsequently calculated using the VWC data to account for site-to-site variations.

For the purposes of this calculation, the mean daily 'lower' and 'upper' limit of soil moisture represented the extreme values in the data obtained from each site.

The numbers of plants emerged per m^2 per plot at each monitoring date were compared between depths and between dates at each site using repeated measures analysis of variance (ANOVA; GenStat version 16, VSN International Ltd, UK). To further explore emergence patterns, the distribution of emergence times for each plot was analysed by a probability distribution. For the Hawke's Bay site, the emergence curves were reasonably symmetrical, so a normal distribution was used. For the Canterbury site, the majority of emergence had occurred by 40 days after sowing (DAS), except in the shallow treatment where a second cluster of plants emerged 50 to 80 DAS. The emergence of these plants was behind that of the majority of the crop and was therefore excluded from the statistical analysis. Analyses of the emergence curves were conducted up to 41 DAS. Even then, the data were skewed and were fitted using a log-normal distribution. The emergence curves estimate a time to 50% emergence, a spread of the other percentile around the time to 50% emergence, and an estimated total number of emerging plants for each plot. These estimates were also compared between depths using Kruskal-Wallis tests.

Results

Crop survey

A wide range of establishment outcomes were observed across the 14 monitoring sites (Figure 1). Across all sites, the average plant population at the final harvest was 69% of target population, ranging between 31 and 96%. In most cases, plant populations were relatively stable once reaching a maximum at a given site. However, in three of the 14 crops (Sites 1, 12 and 13) there was a clear decline in plant populations during the season.

The purpose of this study was not to identify quantitatively which factor was most prevalent in good or poor establishment, but instead consider the effects of these outcomes on yield and root size. No relationship between plant population targets and resulting variability in establishment outcomes was found. Inasmuch, higher target planting populations were as variable as lower target planting populations. A variance components model was used to apportion differences in variability to either between sites, within a site and over time. These analyses indicated that 82% of the variation in observed values was due to site-to-site differences, 10% to plot-to-plot differences, and 8% to differences over time.

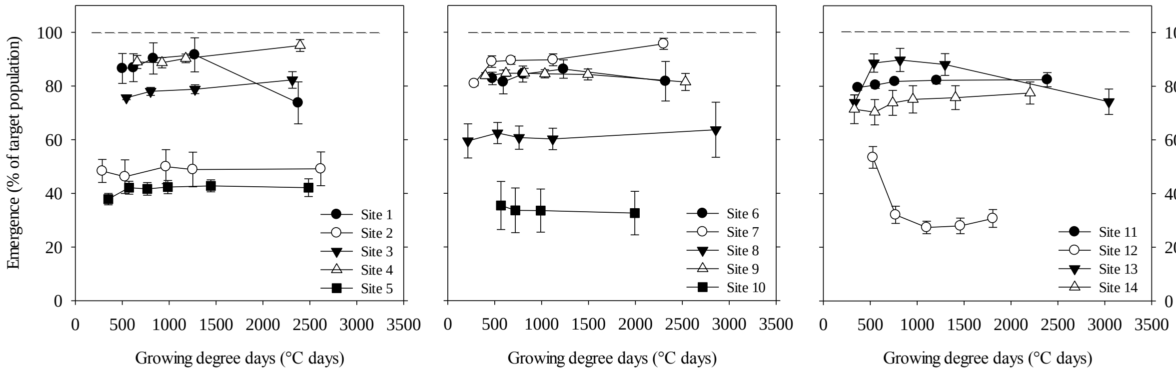

Figure 1: Emergence patterns for the 14 surveyed carrot crops expressed as percentages of target populations, 2013-14 in Canterbury (Sites 1-7, 9, 11, 14) and Hawke's Bay (Sites 8, 10, 12, 13). Vertical bars indicate the standard error of the mean (n =4)

A comparison of modelled yields using the measured plant populations and target plant populations is displayed in Figure 2a. A consistent harvesting date of 2250°C days (GDD) was used to give a common point of comparison (except for Sites 5 and 10, with 1900 and 1740°C days respectively, reflecting early commercial harvests). Across the 14 sites, modelled yields using the measured plant populations were on average 7% lower (on average 141 t/ha) than what was possible had the target population been achieved (152 t/ha). Differences in potential yield ranged from a gain of 3 t/ha (Site 7) to a loss of 38 t/ha (Site 12). The gain in yield associated with lower population appeared related to soil water dynamics in the model and site-specific conditions, whereas the more commonly observed loss of yield was associated with low plant establishment. The model also demonstrated the potential effect of variable establishment on individual root size outcomes. Generally, as population decreased, individual root size increased. In most cases this resulted in carrots that were considerably larger than would have been achieved (and was desirable) at the target plant population size (Figure 2b). In some cases (e.g. Sites 2, 5 and 12), an increase in individual root size was insufficient to counteract reduced populations and total yields were substantially less than those predicted for the targeted population size.

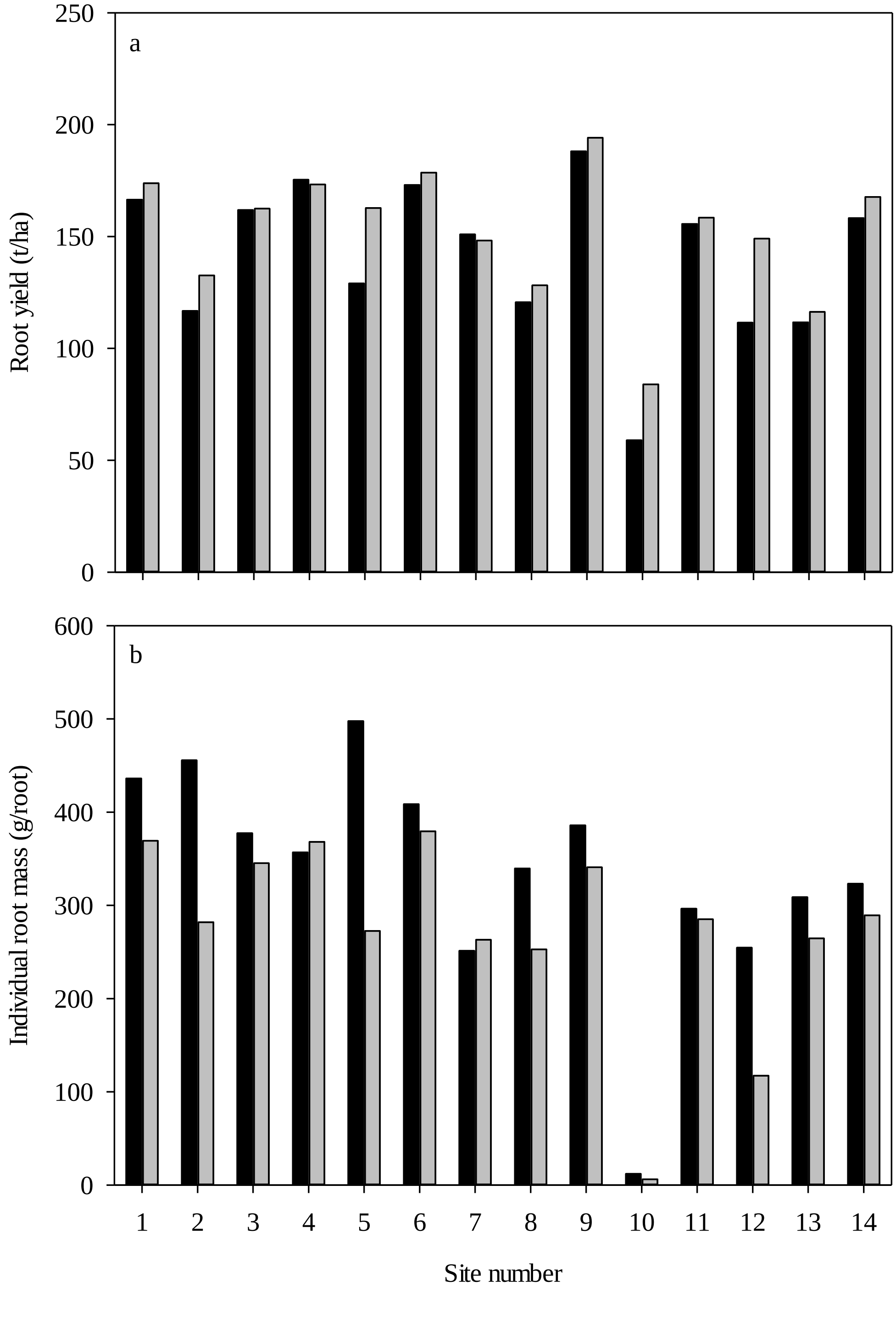

Figure 2: Simulated yield (a) and root mass per carrot plant (b) for the achieved (black bars) and target (grey bars) populations at 2250°C days, 2013-14 in Canterbury (Sites 1-7, 9, 11, 14) and Hawke's Bay (Sites 8, 10, 12, 13). Results for Sites 5 and 10 are presented for 1900 and 1740°C days respectively because of their short growing season.

Sowing depth experiments

Plant emergence was monitored twice weekly until populations had stabilised (Figure 3). For the Canterbury site, the population had generally reached a plateau by 250°C days (23 DAS), compared with Hawke's Bay site where all treatments reached a plateau by 200°C days (15 DAS) (Figure 3). At the Canterbury site a late increase in emergence occurred from 561 to 935°C days (44 to 72 DAS) and resulted in an additional 9 plants/m^2 for the shallow treatment (data not shown). During this period there were no changes in population in the other two treatments.

At the Canterbury site the deep sowing treatment reached 50% plant emergence at 186°C days (19 DAS), which was significantly (P=0.007) quicker than the emergence in the shallow treatment, at 222°C days (21 DAS) (Figure 3). The deep treatment had the highest final established plant population, of 29 plants/m^2, which along with the normal treatment (27 plants/m^2) were significantly (P=0.006) higher than that in the shallow treatment, with 16 plants/m^2. All plots were still well below the target population of 41 plants/m^2. At the Hawke's Bay site the opposite pattern in emergence was observed. Time to 50% emergence for the shallow treatment was 147°C days (11 DAS), which was significantly (P=0.004) quicker than those for the normal and deep treatments, with 158 and 166°C days (12 and 13 DAS) respectively. The maximum number of plants that emerged followed similar patterns, with the shallow treatment achieving 145 plants/m^2, significantly (P<0.001) higher than the numbers in the normal and deep treatments, with 133 and 116 plants/m^2 respectively. The target population at the Hawkes Bay site was 140 plants/m^2.

Sowing depth had no significant effect on plant spacing or index measures at the Hawkes Bay site (Table 1). However, at the Canterbury site the shallow sowing treatment resulted in a significantly (P=0.01) higher mean plant spacing of 178 mm, compared with 146 and 139 mm for the normal and deep treatments, respectively (target spacing was 96 mm). The shallow sowing treatment at this site also produced the lowest (P=0.031) percentage of plants sown at the correct seed spacing (i.e. single) of 31%, compared with 46 and 48% for the normal and deep treatments respectively. The shallow treatment also had the highest (P=0.037) percentage of gaps greater than 1.5 times the target spacing (considered to be a 'missed plant') with 67%, compared with 51 and 49% for the normal and deep treatments respectively.

The Canterbury site soil temperatures reached a minimum of 1.8°C and a maximum of 37°C over the first 50 DAS, compared with values at the Hawke's Bay site, which reached a minimum of 3°C and a maximum of 45°C (Figure 4a and 4b). The Canterbury site had a total of three days above 35°C during this period, compared with the Hawke's Bay site, which had a total of 16 days. Overall ERPAWC was higher at the Hawkes Bay site, especially within the first 15 DAS (Figure 4c). More frequent water replenishment (rainfall and irrigation events) at the Hawkes Bay site meant that estimated ERPAWC was also more consistent throughout the season and therefore by comparison, the Canterbury site appeared to experience much larger water deficits.

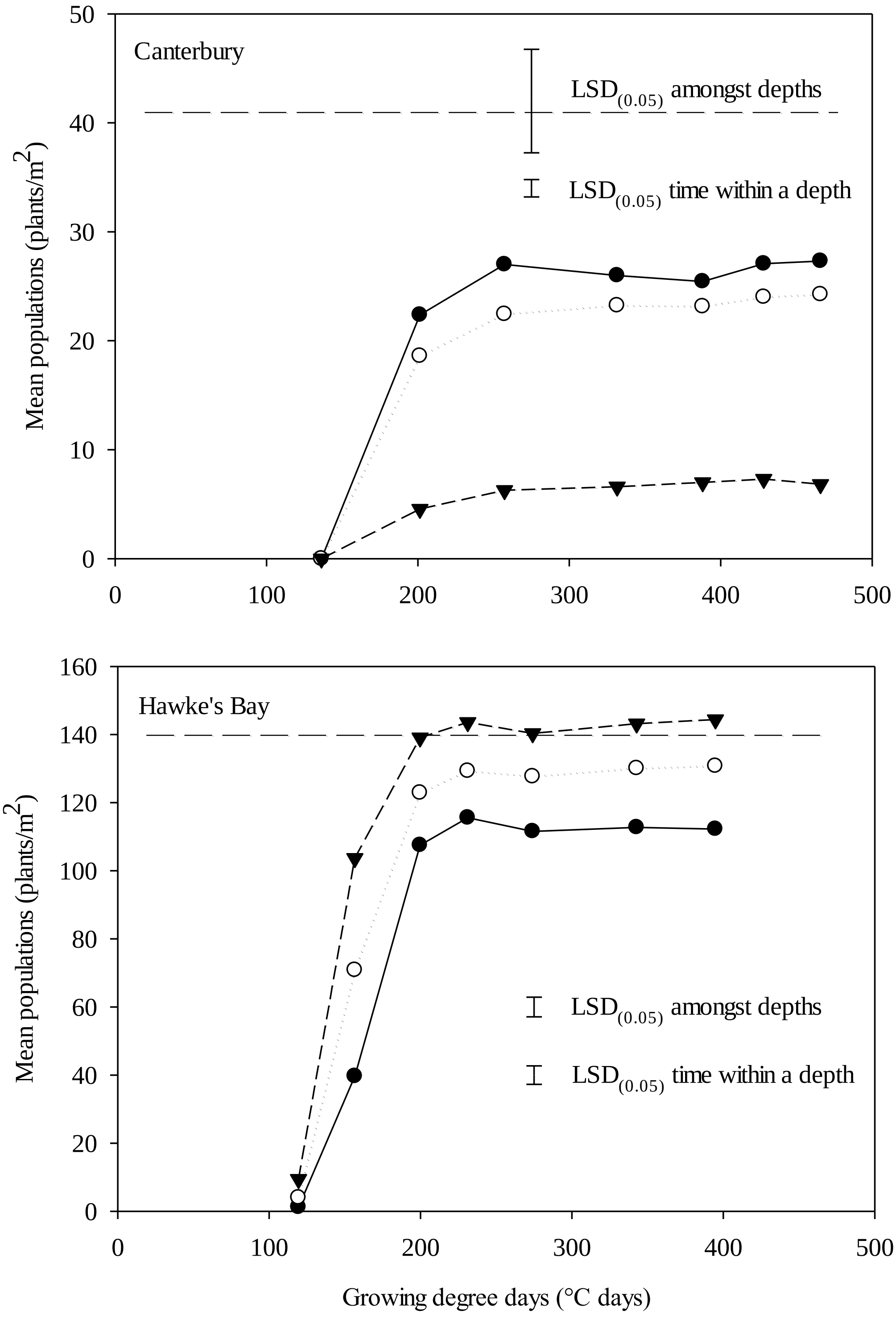

Figure 3: Mean carrot populations (plants/m^2) sown at deep (●), normal (○) and shallow (▼) sowing depths in a) Canterbury, and b) Hawke's Bay over the first 500°C days after sowing, 2015-16. Dotted line represents target population. Bars represents LSD (5%), either for comparing amongst depth treatments or across sampling times for a given depth treatment.

Table 1: Plant spacing dynamics (mean spacing, coefficient of variation (CV), and percentage of plants categorized as singles, doubles or misses) for process carrots sown at shallow, normal and deep sowing depths in Canterbury and Hawke's Bay, 2015-16.

	Mean within row plant spacing (mm)	CV (%)	Single index (%)	Multiple index (%)	Miss index (%)
Canterbury					
Shallow	178	57	31	2.2	67
Normal	146	69	46	2.8	51
Deep	139	71	48	3.5	49
P-value[1]	0.010 (24)	0.039 (11)	0.031 (13)	0.696 (3.2)	0.037 (14)
Hawke's Bay					
Shallow	49	66	64	5.4	31
Normal	51	73	62	5.1	33
Deep	49	66	65	5.0	30
P-value[1]	0.668 (9)	0.409 (13)	0.845 (10)	0.823 (1.6)	0.835 (10)

[1] $LSD_{(0.05)}$ values are shown in parentheses

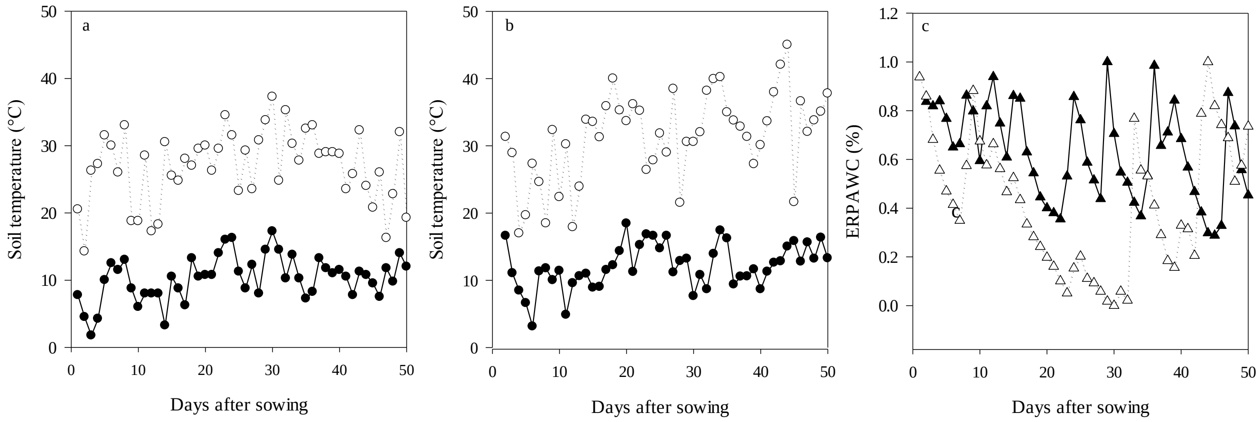

Figure 4: Daily minimum (●) and maximum (○) soil temperature at 20 mm depth for a) Canterbury and b) Hawke's Bay, 2015-16. Estimated relative plant available water content (ERPAWC) at 20 mm depth (c) for the Canterbury (Δ) and Hawke's Bay (▲) sites over the first 50 days after sowing.

The deep sowing treatment had a significantly (P=0.005) lower total root yield, of 93.9 t/ha, compared with those of the normal and shallow treatments of 104.3 and 101.5 t/ha respectively (Table 2). The deep treatment yielded 60.6 t/ha marketable root yield, 14.6 t/ha less (P=0.022) than the shallow sowing treatment. Dry leaf biomass was significantly (P=0.006) higher in the normal sowing treatments, with 3.6 t/ha, 0.3 and 0.4 t/ha more than the shallow and deep sowing treatments respectively. Final plant populations were significantly (P<0.001) higher in the shallow treatment, with

1,393,000 plants/ha, than in the normal and deep treatments, with 1,247,000 and 1,074,000 plants/ha respectively. Mean root length was significantly (P=0.01) longer in the deep treatments (175 mm) than in the normal and shallow treatments (166 and 164 mm respectively). Mean individual fresh root mass was significantly (P=0.022) higher in the deep treatments (90.4 g/root) than in the normal and shallow treatments (84.1 and 79.2 g/root respectively).

Table 2: Plant population, root yield (total and marketable), crop biomass (root and leaf) and root size indicators (length, width and individual mass) at the commercial harvest of process carrots in the sowing depth experiment, Hawke's Bay only, 2015-16. DM = dry matter. Mkt. = marketable, dmtr = diameter, indiv. = individual.

Treat-ment	Population (plants /ha)	Total root yield (t/ha)	Mkt. root yield (<30 mm dmtr, t/ha)	Root biomass (t DM /ha)	Leaf biomass (t DM /ha)	Mean root length (mm)	Mean root dmtr (mm)	Mean indiv. fresh root mass (g)
Deep	1,074,000	93.9	60.6	13.8	3.2	175	26.9	90.4
Normal	1,247,000	104.3	64.4	14.9	3.6	166	26.7	84.1
Shallow	1,393,000	101.5	75.2	14.0	3.3	164	25.9	79.2
P-value[1]	<0.001 (82,000)	0.005 (5.5)	0.022 (10.0)	0.052 (0.9)	0.006 (0.2)	0.010 (6)	0.176 (1.2)	0.022 (7.4)

[1]$LSD_{(0.05)}$ values are shown in parentheses.

Discussion

Crop survey

In the crop survey of the 14 sites, population differences were typically evident within 3-5 weeks after sowing and these differences generally remained stable over time. This suggests that once crops had emerged they were fairly resistant to different biotic and abiotic stresses across the different sites. The causes of poor establishment could have been related to a mix of seed quality, management and/or environmental conditions during germination and the early seedling stage. Where large in-season decreases in plant populations were observed either for the whole site (e.g. Site 12) or plots within a site (e.g. Site 1 and 13, demonstrated by high standard errors across the season), fungal disease or extreme weather events such as hail were observed. The range in establishment outcomes across the 14 sites, of 31 to 96% of target population, was similar to that reported for carrot production in the Netherlands (Schoneveld, 1990). In that work, the variability was the result of differences in seed quality and environmental conditions.

Establishing a plant population well below target can have a major influence on total yield, individual root size and marketable yield (Finch-Savage, 1988). This is particularly important in the processing sector, where root size can have a significant impact on processing efficiencies. Model predictions using measured and targeted plant populations across the monitoring sites showed a very clear effect of establishment outcomes on key productivity indicators. Sites with a lower than targeted planting population were predicted to have an average yield loss of 11 t/ha; in the worst case, predicted yield loss was 38 t/ha. In addition to the lost gross productivity at the sites, a strong effect on root size was also predicted. At half the sites, roots were >15% larger at the achieved populations than at the target population, and at four of these sites roots were >50% larger at the achieved populations than at the target population. However, at some sites this increase in individual root mass still failed to compensate for the potential yield loss associated with poor establishment. A high proportion of large carrots is less of a concern for juicing and dicing end-uses, but can have a big impact on processing efficiencies for rings and baby carrots.

A higher proportion of oversized carrots can also lead to quality issues, as there is a greater chance of splitting. Splitting can lead to an increased percentage of rotten roots and soil contamination. Conversely, when plants are established too close together, increased intra-plant competition can result in smaller carrots that do not meet processing criteria. Both these sub-optimal situations lead to a decrease in marketable yield and net returns to growers.

Sowing depth experiments

Although both experiments targeted the optimal sowing depth for their particular site, very different establishment trends were observed (Figure 3). At the Canterbury site the deep sowing treatment achieved the best establishment, whereas at the Hawke's Bay site the shallow treatment performed best. Irrigation management differed substantially between sites, with the Hawke's Bay site receiving 10 mm irrigation twice weekly until the crop had established, compared with the Canterbury site, which did not receive any irrigation until 71 DAS. The lack of early irrigation coupled with little rainfall during the germination period was responsible for the very poor establishment observed at the Canterbury site. The late increase in plant populations observed in the shallow treatment at the Canterbury site, probably reflected rainfall received after the initial germination period. This suggests that for the viable seed that still remained, soil moisture was the limiting factor to germination. This late emergence of plants would have been unlikely to have contributed heavily to marketable yield, as the plants would have been approximately 50 days behind the rest of the crop.

Application of irrigation or heavy rainfall soon after sowing can be risky, as surface capping (crusting) can occur. Variable and reduced emergence occurs with the presence of crusting and is more pronounced with dry crusts of 5 mm or greater (Tamet *et al.*, 1996). Repeated irrigation is required to reduce the risks of surface capping and should continue until the crop has fully emerged. Importantly, no evidence of surface capping was observed at either site.

For the Canterbury site, increased soil temperatures not only dried the soil surface, thus delaying imbibition and germination, but when soil temperatures exceeded 35°C for prolonged periods, germination percentage may have decreased, as was reported by Nascimento and Pereira (2007). Sowing deeper proved beneficial at the Canterbury site, as greater soil moisture was available, and lower soil temperature probably aided establishment. The high level of variability in soil moisture and temperature during the emergence phase at the Canterbury site, is likely to have contributed to establishment that was well below the target population at all three sowing depths. Under these conditions seed may have partially germinated before re-drying, subsequently reducing the seed viability, as demonstrated in other species (Koster and Leopold, 1988).

Early, frequent irrigation at the Hawke's Bay site appeared to result in good soil moisture for germination, with plant establishment being highest in the shallow treatment. Although the Hawke's Bay site experienced a greater number of days above 35°C than the Canterbury site (up to 50 DAS), soil temperatures did not exceed 35°C in the first 15 DAS, by which time the population had stabilised. The culmination of warm soil temperatures and adequate soil moisture meant that rapid and uniform plant establishment occurred. Although soil moisture was adequate for emergence at the deeper sowing depth, it is likely that the combination of sowing depth and soil moisture created lower soil temperatures, and therefore increased time to emergence and subsequent smaller established populations.

Another contributing factor to low soil moisture at the Canterbury site was the use of barley as a wind break to protect the carrots. Standing barley residue can help to protect carrot seedlings from extreme rainfall and wind events (Brainard and Noyes, 2012). Barley at the Canterbury site was actively growing up until the time it was sprayed out on 5 January (63 DAS), thus increasing competition for water when there was already low soil moisture, and subsequently reducing carrot germination.

In terms of overall productivity, the shallow sowing depth treatment at the Hawke's Bay site had the highest marketable yield of all treatments. This appeared most closely related to this treatment having the highest established populations. No yield data were collected from the Canterbury site, but visual observations made at the site during the season indicated that yield loss related to shallow sowing appeared to be considerable. In addition to the loss of total yield, marketable yield would have also probably been affected because of the very low populations.

Conclusions

Crop survey results demonstrated that process carrot establishment can be highly variable in both Canterbury and Hawke's Bay in New Zealand. Simulation analysis indicated that in fields where poor establishment was observed, substantial losses of total and marketable yield could result. Two targeted trials demonstrated that sowing depth in conjunction with environmental factors had a significant impact on crop establishment. Careful consideration is required to ensure that soil moisture and temperature are optimal for seed imbibition, germination and establishment, in conjunction with seedbed preparation that provides adequate seed/soil contact. Manipulation of these factors through the use of well-timed irrigation can help to ensure that rapid emergence and establishment of carrots are achieved. Successful establishment is essential to achieving high marketable yields, provided that correct plant spacing is achieved.

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References

Brainard, D.C. and Noyes, D.C. 2012. Strip Tillage and Compost Influence Carrot Quality, Yield, and Net Returns. *Hortscience* 47: 1073-1079.

Finch-Savage, W.E. 1988. The potential for seed, sowing and seedbed preparation treatments to improve the production of uniformly-sized carrot roots for processing. *Acta Horticulturae*: 181-188.

Kachman, S. and Smith, J. 1995. Alternative measures of accuracy in plant spacing for planters using single seed metering. *Transactions of the ASAE* 38: 379-387.

Koster, K.L. and Leopold, A.C. 1988. Sugars and desiccation tolerance in seeds. *Plant Physiology* 88: 829-832.

Nascimento, W.M. and Pereira, R.S. 2007. Preventing thermo-inhibition in carrot by seed priming. *Seed Science and Technology* 35: 504-507.

Reid, J.B. 2005. The carrot calculator: A decision support tool for carrot crop management. *Acta Horticulturae* 670: 131-136.

Schoneveld, J.A. 1990. Research aimed at a reliable field emergence of carrots. *Acta Horticulturae* 267: 199-208.

Tamet, V., Boiffin, J., Durr, C. and Souty, N. 1996. Emergence and early growth of an epigeal seedling (*Daucus carota* L.): Influence of soil temperature, sowing depth, soil crusting and seed weight. *Soil & Tillage Research* 40: 25-38.