Final report FV46a

Effect of irrigation, development and variety on mechanical stress and tissue strength in carrot storage roots

PRINCIPAL WORKERS

HRI WELLESBOURNE

Dr C C Hole (Author of report)

Dr A McGarry

Mr R L K Drew MSc

Mr N R Parsons BSc

AUTHENTICATION

I declare that this work was done under my supervision according to the procedures described herein and that this report represents a true and accurate record of the results obtained.

Signature David Gray

Dr D Gray

Head of Crop and Weed Science

HRI Wellesbourne

Date 19/6/96

Final Report	1996
Project Number	FV46a
Project Title	Effect of irrigation, development and variety on mechanical stress and tissue strength in carrot storage roots
Project Leader	C C Hole (A McGarry - years 1 and 2)
Location of Project	HRI, Wellesbourne
Project Co-ordinator	
Date completion due	31 March 1995 - extended to 31 March 1996
Key words	carrot, splitting, breakage, fracture, root age, root weight, irrigation, water status, toughness, strength, cell size, cell wall

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RELEVANCE TO GROWERS AND PRACTICAL SECTION

Application

The purpose of the project was to establish relationships between carrot root water relations and root fracture properties and to measure variation in root strength with a view to devising methods of reducing damage in commercial practice.

The principal findings are:

- ☞ the strength of carrot root tissue increases with time, particularly towards the end of the season, but is not affected by irrigation treatment and varies little between the varieties investigated.

- ☞ the effects of irrigation on splitting in the ground are not the result of alterations to root water status, but are probably due differences in growth rate.

From a practical point of view:

- ☞ it is important to control root growth against this background of changing root strength to avoid both splitting in the ground and harvest damage.

- ☞ This can be done by effective scheduling of irrigation to achieve most rapid growth when the roots are likely to be at their strongest and allowing growth to diminish prior to harvest.

RELEVANCE TO GROWERS AND PRACTICAL SECTION

Summary

Purpose

The purpose of the project was:

- ☞ to establish relationships between carrot root water status and root fracture properties with a view to devising methods of reducing damage in commercial practice.

The project aimed:

- ☞ to examine changes in water status as a means of quantifying the build up of mechanical stress within storage roots in relation to the supply of irrigation water.
- ☞ to measure changes in susceptibility of root tissue to fracture and in inherent strength of the tissues in relation to variation in irrigation regime and root development.

Results

Mechanical damage to carrot roots is manifested either as transverse breakage or longitudinal splitting of the outer sheath of tissue. Both kinds of damage occur as a result of handling processes at harvest, but splitting may also take place spontaneously during growth.

The work described in this report emphasizes splitting rather than breakage, because breakage is very much more a consequence of mishandling, root shape and root size. In contrast, splitting is influenced to a much greater extent by the propensity of root tissue to fracture.

The outer sheath (or phloem parenchyma) of carrot roots grows from the inside. Consequently, the actively expanding new cells exert considerable mechanical stress on the older tissues outside them. The amount of stress depends on the turgidity of the cells. The likelihood of splitting depends on the strength of the cell walls and the ease with which the skin of the roots becomes notched. This latter process is akin to the procedure of scoring glass so that stress is concentrated in this "notch". It will then break more readily at this point. In this work, bulk strength of tissue has been

estimated because this is more readily amenable to measurement than the location, occurrence and susceptibility to notching.

Strength of carrot root tissue increased slowly during the growing season and then markedly at the end of the season in three varieties (cvs Nandor, Nairobi and Narman). In contrast, susceptibility to fracture and turgor showed relatively little systematic variation with time. Imposition of different irrigation treatments and variety had little effect on turgor, tissue toughness or strength.

Nevertheless, substantial early irrigation and moderate irrigation throughout the life of the crop led to a greater proportion of roots which split during growth, than if irrigation was left until later in the season. This effect was not related to any change in the turgidity of the tissue. It was concluded that greater incidence of splitting was brought about by more rapid growth stimulated by the availability of water rather than increased root turgor. From a scientific point of view, the absence of differences suggests that more appropriate techniques to measure mechanical stress in whole roots need to be developed.

Growth splitting was associated with roots larger than 80g (a further indication that differences in mechanical stress results from different rates of expansion growth rather than differences in turgor) and in general the average root size of those that are damaged in drop tests is greater than those that remain undamaged.

Combination of irrigation and novel methods of soil tillage to improve root quality under commercial conditions in these studies met with limited success. One experiment suggested that mean root weight (and thus yield) was increased without any increase in post-harvest damage. However a second experiment done on a larger scale distinguished no clear-cut effects. This may have been due more to limitations place on experimental procedure by commercial decisions than to shortcomings in the treatments themselves.

RELEVANCE TO GROWERS AND PRACTICAL SECTION

Action points for growers

From a practical point of view this work has shown that:

☞ **substantial irrigation applied early** in the life a carrot crop and **moderate irrigation applied evenly** throughout the life of the crop **are likely to lead to a greater proportion of roots which split during growth**, than if irrigation is left until later in the season.

☞ **root strength increases as the season progresses.**

Irrigation applied early or during mid-season when environmental conditions are suitable for rapid growth places roots under great mechanical stress at a time when they are at their weakest. By delaying irrigation until later, the period of most rapid growth can be timed to coincide with greater strength. Thus to avoid greater possibility of growth splitting the aim should be to:

☞ **schedule root growth against this background of increasing root strength.**

For splitting and breakage at harvest:

☞ **mechanical stresses arise in the roots in the same way as for growth splitting, so it may be advisable to avoid rapid growth immediately prior to harvest.**

EXPERIMENTAL SECTION

INTRODUCTION

Carrots are susceptible to two major forms of damage at harvest, transverse breakage and splitting (longitudinal cracking). Breakage is largely a man-made problem caused by insufficient care being exercised during harvesting and handling, but splitting can occur in a growing crop and must, therefore, represent a consequence of carrot growth and development. Growth splitting is generally a relatively minor problem but can occasionally reach economically significant levels. Whilst supplementary irrigation can increase yield, there is evidence that heavy irrigation can induce extensive growth splitting, especially if it follows prolonged periods of drought. The time at which irrigation is applied can also adversely affect root colour, another key quality attribute.

Carrot storage roots are formed by the secondary growth of the vascular cambium which produces a "sheath" of phloem parenchyma tissue to the outside and a "core" of xylem parenchyma to the inside. The phloem consists of tightly-packed, thin-walled cells. Since carrot tissue fractures by cell wall breakage, tissue toughness is determined largely by turgor pressure, cell wall volume fraction, cell wall strength and the degree of adhesion between adjacent cells. Adhesion affects the transmission and concentration of stresses. As storage root expansion proceeds, cells enlarge and cell wall volume fraction drops. Provided that cell wall composition does not change during growth, tissue strength would be expected to decrease during this time. At high turgor and during rapid growth, the tissue becomes more brittle and prone to fracture, because of increased mechanical stress that builds up.. When growing on sandy or abrasive soils, carrots may develop numerous superficial scratches or notches which act as stress concentrators, dramatically weakening the tissue. At high turgor, tissue toughness is decreased (so the tissue is more likely to be notched) and notches will have sharper tips, making them more efficient stress concentrators. As a result, supplying plentiful irrigation to rapidly expanding roots growing in a sandy soil might be expected to induce widespread growth splitting.

At harvest, removal of roots from the soil also removes any role of containment of stress that the soil may play. Mechanical stresses within roots must then be borne solely by the root tissues. During harvesting and packing, the roots receive impacts

which provide additional mechanical stress. This combined with the internal stresses already present may be sufficient to overcome the strength of the outer tissues, leading to splitting and/or transverse breakage.

DISCUSSION OF RESULTS

The build-up of mechanical stress in any growing tissue must be dependent on the availability of water and on the pressure exerted on cell walls (turgor) by the cell's ability to draw in water. In this way, plant tissues achieve rigidity. Whether this is beneficial depends on the context, but clearly a rigid structure may also be a very brittle one, particularly if the "solid" part of the structure (i.e. the cell walls) does not posses great strength. For this reason, the work in this programme has examined water status of roots and the ease (or not) with which root tissue fractures as a means of assessing the presence of mechanical stress within roots to see if this relates to circumstances in which damage varies. It has also looked at tissue strength, since variation in damage may depend on this as well. In short, when stress exceeds strength, the outcome is damage.

The toughness of tissue reflects its brittleness. This has been measured by the energy required to fracture the outer sheath of carrot phloem parenchyma tissue when a controlled crack is formed by driving a wedge through it. Turgid tissue would be expected to be more brittle (glass-like) than flaccid tissue and carrot is no exception (Fig. 9 and McGarry, 1993). Thus less energy is required to crack more turgid carrots. It therefore may be expected that variation in susceptibility to splitting or harvest damage might be related to root water status and to measurements of fracture toughness. Generally this was not the case for the experiments described here. Turgor varied very little during development (Figs 2, 8 and 17) or with irrigation treatment (Fig. 8). A previous comparison of varieties (McGarry, 1993) revealed greater turgor in the split-resistant cv. Camden than in split-susceptible cv Tamino: the opposite of expectation. A similar, significant observation (Fig. 17) was made when comparing cvs Narman (more damage-resistant) and Nairobi (less damage-resistant), though the difference is small. This would suggest that turgor may not be a major discriminant of variation in damage susceptibility under field conditions. This is further supported by the absence of any relationship between mean fracture toughness and mean water or turgor potentials (Fig. 11 and Table 3) for different irrigation regimes and root ages. Clearly, however, irrigation regime does affect the incidence of splitting (Fig. 5), with later irrigation being associated with less splitting. Not only did turgor not show any relationship with splitting, but there was not a lot of evidence for increased fracture

toughness in the late watered roots, apart from a barely significant increase at 120 days from sowing (Fig. 10). An absence of any relationship with turgor may be explained on the basis that mechanical stress results from the rate of division and radial expansion of cells and thus, growth of root tissue rather than pressure exerted within cells. An observation which may reflect this is that the outer layers of cells of carrot roots provided with irrigation early in the season exhibited distinct tangential elongation compared with roots from later irrigation treatment. In other words, they appeared to be more stretched. The increased fresh weight of roots irrigated early would support the view that growth was more rapid (Fig. 4).

Failure to observe any indication of split-susceptibility from measurement of fracture toughness may have occurred because measurement on excised tissue samples does not include stresses present in an entire root. Turgor may also be different in excised tissue, for the same reason. These assertions lead one to conclude that it is important to develop ways of estimating mechanical stress present in an entire root. Only then will discrimination between different factors affecting damage susceptibility be properly represented. The failure to demonstrate any relationship between turgor and damage susceptibility in this programme does not, of course, rule out the use of methods of reducing turgor as means of alleviating mechanical stress (HDC 1993).

Mechanical stress need not build up evenly over the root. It can become concentrated in weak points and/or imperfections at the surface. Such local concentration in "notches" is likely to be greatest in the outside layers and may readily overcome the strength of the tissues. Carrot phloem parenchyma is notch sensitive (Fig. 1), which means that its strength decreases with an increase in the relative size of the notch and it becomes increasingly susceptible to fracture. The occurrence and importance of "naturally-occurring" notches has not been studied in this work. The view was taken that an evaluation of phloem tissue strength would be of equal importance and more rewarding since, whether notched or not, variation in general tissue strength may still determine the likelihood of splitting.

The principal observations to emerge on variation in tissue strength are that it

- ☞ **gradually increased with root age (time from sowing), with a particularly rapid rise at the end of the season** (Figs. 12 and 15),
- ☞ **was unaffected by irrigation regime** (Fig. 12)
- ☞ **was greater for later sown carrots** (Fig. 15) and
- ☞ **was similar in varieties contrasting in their susceptibility to damage** (Fig. 15).

The end-of-season rise has been shown on two separate occasions and for three varieties and so would seem to have some generality. It is of interest for two reasons. Firstly it should provide a useful system for investigating changes in cell wall chemistry associated with changing tissue strength, since the proportion of cell wall in the tissue was falling at this time (Fig. 14). Secondly, the rise may be environmentally dependent. This latter reason raises the possibility that strength may be manipulated by husbandry. Both of these merit further study. The absence of any effect of irrigation on strength suggests that cell size (and thus cell wall fraction) and cell wall composition were probably unaffected by water availability. It is perhaps surprising that two varieties (Narman and Nairobi) which show differences in damage susceptibility in drop tests (data not shown) should not differ in strength. These varieties were very similar in length and diameter (unpublished information) - an important consideration when making comparisons by drop test. This underlines the importance of establishing reliable methods of measuring the mechanical stress present in whole roots in order to compare more fully variation in damage under different circumstances.

As has already been indicated, tissue strength must depend on the collective strength of its component cell walls since splitting results from cell wall fracture and not cell separation (McGarry, 1993). For this reason one might reasonably expect relationships between strength, cell size and the amount of cell wall present. For the experiment in year 2, cell diameter increased with root age (Fig. 13), while the amount of cell wall (expressed as apoplast fraction, Fig. 14) decreased. Since these trends are the opposite of what might have been expected, it has been suggested that changes in cell wall composition must therefore have contributed to the strengthening (McGarry 1994 and see above). In contrast, in year 3 the fraction of cell wall increased with root age (Table 8) and thus correlated with changes in strength. Cell wall fraction also

showed a difference between the varieties, being slightly larger in the less susceptible cv Narman. Microscopical inspection of a limited number of roots suggested that cells of cv Narman were smaller than those of cv Nairobi. This would correspond with the observed larger proportion of cell wall for cv Narman and with its greater dry matter content (Table 7). It is therefore surprising that tensile strength of phloem parenchyma tissue from this variety was no greater than that for cv. Nairobi (Fig. 15) and that there was no difference in fracture toughness of their tissues (Fig. 16). It is possible that changes in cell size and in cell wall fraction have only a small consequence for tensile strength and that fracture toughness of tissue blocks simply did not represent circumstances in the whole root, as discussed above.

☞ **The practical message which emerges from these experiments is that susceptibility to damage in carrot roots (during growth and at harvest) results from the build up of mechanical stress due to expansive growth. In order to avoid large stresses it is therefore important to control the rate at which tissues expand i.e. the rate of growth.**

One means of doing this is by judicious use of irrigation; both amount and timing. Set against a background of changing tissue strength with root age, it clearly makes good sense to plan for most rapid growth when the tissues are stronger i.e. delaying this, if possible, until later in the season. However, because rapid growth creates greater mechanical stress it must be curbed some time in advance of harvesting.

The practical use of irrigation and soil cultivation is likely to affect growth rate through water availability throughout the soil profile. In year 1 both irrigation and soil tillage together increased average root size, while having little effect on post-harvest damage. This is an important observation, because both growth splitting (Table 5) and susceptibility to post-harvest damage are related to root size (Mean fresh weights were 140g for damaged and 105g for undamaged roots at final harvest of the second sowing, with a l.s.d. at p=0.05 of 25.9). Therefore increased mean root size from agronomic procedures might be expected to be associated with increased damage. Irrigation alone appeared less effective in altering mean fresh weight than did soil tillage (Table 1).

In year 3 the effects of these procedures were not as consistent or clear from the study of application on a commercial scale. Part of this uncertainty probably resulted

from the limited difference in irrigation application that was applied in conjunction with soil tillage. Another reason for the absence of any great treatment effects on roots harvested in January 1996 for retail, was that, for commercial reasons, this took place later than planned. Thus there were several months between the application of treatments and final harvest. Samples taken in the autumn did suggest that lower irrigation led to higher mean root weight and, on one of these sampling occasions, tilling the soil increased root weight (Tables 9,10,11). Differences between specific tillage/irrigation treatments were not consistent at different harvest times. No consistent differences in mechanical and physiological properties that might be relevant to damage susceptibility were measured at this time (Tables 9,10) or at final lifting in January 1996 (Table 11). At final lifting there were no obvious effects of either tillage or irrigation treatments on root fresh weight (Table 11), incidence of damage in the raw feed to the pack line (Table 13) or in susceptibility to damage of packed marketable roots in a drop test (Table 14). The level of damaged roots in the packs after transit was fairly high (Table 14) indicating that damage is a problem which persists throughout the chain. While mechanistic reasons can be advanced for the use of irrigation and soil tillage to reduce the incidence of damage during harvesting and handling operations, the present evidence associating these on a commercial scale is unconvincing. This may have resulted more from difficulties in maintaining an effective programme of treatment, assessment and harvest schedule than from limitations of the agronomic practices themselves.

Some effects of treatment on colour were observed. In year 2, late irrigation resulted in roots that were more orange (Table 6) , while soil tillage in year 3 was associated with increased redness of samples removed in the autumn (Table 12). This latter effect was not evident at commercial harvest of the crop in January of the following year.

RESULTS

Year 1

The strength of carrot phloem parenchyma as estimated by mechanical stress at failure was shown to be sensitive to the presence of a notch (Fig. 1). There was clear decrease in failure stress with relative notch size. Simply, this means that carrot tissue is likely to fracture more readily if it has imperfections in its outer layers. Failure stress of notch-insensitive tissue would not be decreased by the presence of small cuts and scratches. From electron microscope studies of cell walls it would seem that there is no preferred orientation of splits within the walls.

Tissue strength must depend on the proportion of cell wall that is present, because this forms the only continuous structural matrix throughout the tissue. However, comparison of split-susceptible cv. Tamino and resistant cv. Narman showed no difference in the cell wall fraction (12.8% ±1.89 and 11.9% ±1.49 respectively), so factors other than tissue strength and cell wall fraction must contribute to varietal differences in susceptibility to splitting.

Turgor pressure of carrot root cells, cv. Narman, increased gradually by about 0.15 MPa as the roots aged from 40 to 160 days in a field-grown crop (Fig. 2). Given the size of standard errors associated with this (approx. 0.06 MPa), the rise is barely a significant one.

Combination of tillage and irrigation treatments applied to a commercial crop (cv. Liberno) produced the largest roots of which 11.8% were damaged (Table I). Other treatments gave lower yields and similar incidence of damage resulting in smaller pack-out than for the combined treatment.

Year 2

The work in year 2 was principally based on intensive study of the effect of irrigation on water relations of soil and tap root and on the mechanical properties of the tap root. Timing irrigation differently affected soil water potential (Ψ_{soil}) sufficiently to be confident that the experiment achieved the desired treatment differences (Fig. 3). Soil water potential was relatively constant (at close to 0 kPa) in the early-watered treatment until 115 days after drilling, when it declined. In the evenly-watered treatment it remained reasonably stable at close to 0.5 kPa apart from two spells when it

decreased to below -1.0 kPa. For the late-watered treatment soil water potential began to decrease at about 90 days from drilling, reaching its lowest value of -300 kPa at 115 days after drilling and recovering to nearly 0 kPa at about 145 days.

There was no difference between irrigation treatment in mean root weight until 119 days after drilling (Fig. 4). Thereafter, roots of the early-watered treatment were larger. No splitting was observed before 77 days after drilling (Fig. 5). After this time, the number of split roots increased rapidly in early and evenly-watered treatments. Few splits (< 3%) were present in roots from the late-watered treatment. At final harvest the early-watered treatment produced the highest mean root weight and mean marketable root weights (Table 2). Frequency distributions of root fresh weight for the three irrigation regimes (Fig. 6) showed little difference initially. However towards the end of crop growth, there was a much wider distribution of weight produced by early watering, which gave the largest number of oversized roots (7.2%). Evenly- and late-watered treatments produced very few oversized roots (0 and 2% respectively). In addition, the evenly-watered treatment produced 12.7% undersized roots.

Relationships between root weight, irrigation regime and the incidence of growth splitting are shown in Tables 3-5). Early and even watering resulted in more splits than late watering (Table 4) and splitting was more common in roots > 80 g than smaller ones (Table 5). Late-watering led to roots that were significantly more red and more yellow (*i.e.* more orange) than early-watered roots (Table 6).

The effects of different irrigation regimes on root water potential are shown in Fig. 7. Root water potential increased significantly between 35 and 63 days after drilling for all treatments. Although treatments received different irrigation regimes from 56 days after drilling, no significant difference in root water potential was apparent until 84 days. From this time, it began to decrease for late-watered roots, reaching a lowest value at 119 days, after which it rose gradually in response to increased irrigation. In early and evenly-watered roots, root water potential declined gradually from 105 days until the end of the experiment, when water potential was similar for all treatments. Osmotic potentials (Fig. 7) of the roots effectively mirrored changes in water potential, so treatment differences in turgor potential were very small (Fig. 8), though overall it was in fact significantly greater for the later irrigation treatment than the other irrigation regimes.

Fracture toughness and water potential of phloem parenchyma tissue were negatively correlated within harvests (Fig. 9), The gradients of the regression lines varied considerably between harvests and treatments, particularly at the earlier harvests (< 133 days). Toughness increased in all treatments between 91 and 105 days (Fig. 10), but particularly for the late watering. After this initial increase, toughness remained relatively constant in early- and evenly-watered roots. In late watered roots it decreased again finally achieving a similar level to that in the other treatments. Mean fracture toughness from the different irrigation treatments and times showed no correlation with mean water or turgor potentials (Fig. 11). Also no relationship was evident between the differences in toughness and turgor for successive sampling times i.e. increases and decreases between successive occasions were not related.

In all treatments, tensile strength of tissue from the phloem parenchyma showed a gradual increase with age between 90 and 150 days (Fig. 12). After this time, tensile strength increased dramatically (*circa* 40%) until final harvest at 175 days. There appeared to be little effect of irrigation treatment on tissue strength. The consistently higher value over 90 to 120 days, for the early-watering treatment, probably resulted from an advancement of growth and development.

Failure strain (that is, deformation as a proportion of test piece size) was unaffected by treatment or plant age.

Mean cell diameter increased with plant age (Fig. 13), with no differences between treatments. However, cells in the outer phloem parenchyma of early-watered roots were noticeably more elongated in tangential orientation. The proportion of cell wall (measured as apoplast volume fraction) decreased during this time and was also unaffected by irrigation treatment (Fig. 14). On structural grounds alone, it might be expected that these changes in cell architecture would be associated with a decrease in tissue strength.

Year 3

The end-of-season strengthening observed in cv Nandor in Year 2 was investigated in two other varieties (damage-susceptible cv. Nairobi and damage-resistant cv. Narman) sown on two different occasions, to ascertain the generality of the observation in 1993 and to compare strength in two varieties contrasting in their

susceptibility to damage.

The effectiveness of soil cultivation (tillage) and irrigation treatments in reducing damage and altering tissue mechanical properties was also investigated. The outcome of these treatments was also assessed on commercial samples put through the supply chain.

Tensile strength of the outer phloem parenchyma tissue was similar for both varieties and increased with age for both sowings (Fig. 15). Later sowing resulted in greater tissue strength than earlier sowing for roots harvested at similar numbers of days after sowing. At present, the evidence as to whether this trend resulted from developmental or environmental factors is equivocal. Because of the large numbers of roots measured, there were many significant differences between the two varieties in the measured variables (Figs. 16, 17 and Tables 7,8). However, very few of these differences were large or of importance. Dry matter content in both xylem and phloem tissue was higher in cv Narman which also had a greater ratio of phloem to xylem tissue (Table 7). Fracture toughness was similar for both varieties and sowing dates with the exception of the first harvest of the first sowing in which the tissue was clearly more prone to fracture (Fig 16). This was probably indicative of roots which had accrued fewer day degrees and were therefore less mature. Measurement of water status (Fig. 17) showed that water and solute potentials were lower at the earlier harvests of the first sowing, probably because of inadequate irrigation. Turgor potential, which is more likely to influence mechanical stress in tissues, did not change with time, was about 10% higher overall for cv Narman compared with cv. Nairobi, and showed differences of a similar magnitude between the sowing dates. Apoplast volume fraction (measured for the second sowing only) increased with time and was slightly though significantly greater for cv. Narman than cv. Nairobi (Table 8).

Mechanical and physiological measurements of marketable roots from a commercial crop which had been subjected to different cultivation and irrigation treatments revealed few significant treatment differences for samples harvested either in the autumn or for roots lifted in January for commercial use (Tables 9-11). The fracture toughness of roots harvested at the earliest date appeared to be less than those harvested later. At the first harvest (Table 9), roots from the lower irrigation treatments (C and D) were marginally tougher and had slightly more dry matter than for higher

irrigation. This effect of irrigation on dry matter content was the only consistent feature over all harvest times. A small enhancement of redness of the roots resulted from additional soil cultivation. However, this was detected only for samples harvested on 2 November 1995 and was not present in roots packed for retail (Table 12).

Although mean fresh weights of roots appeared to be affected by treatment for samples harvested in autumn 1995, in that treatment C (cultivated, slightly less irrigation) resulted in largest mean root fresh weight, effects of other treatments were inconsistent between these harvests (Tables 9-11). At final lifting, mean root fresh weight (for all roots and for the marketable fraction) was greatest for treatment A (uncultivated, slightly more irrigation). The only consistent conclusion that can be drawn from these data is that roots from treatment C did not show the lowest mean fresh weight at any time. Combining data across treatments, indicated that root weight at the first two harvests was actually greater for the lower irrigation treatment and that deep cultivation increased root fresh weight at the second sampling. The fraction of roots which was saleable (Table 13) also did not appear to be affected by treatment. Of particular note is that none of the treatments seemed to have affected the proportion of all roots from the packhouse raw feed exhibiting damage (Table 13) nor was there any effect on the susceptibility to damage in a drop test of packed samples which had undergone transport and handling (Table 14). Also the proportion of roots that were damaged after packing was fairly high (Table 14).

EXPERIMENTS

Experiments - Year 1

Carrot material (cv Narman) for experimental examination was obtained from field plots at Wellesbourne and from commercial growers (cv. Liberno). Some beds of the latter variety was subjected to soil cultivation (tillage) and irrigation treatments from about 80 days after drilling. Cultivation at 21 day intervals involved repeated loosening of soil between adjacent rows using a bed injector ("Cultijector") to reduce soil compaction. Irrigation treatments were compromised by heavy rain during the latter part of the season.

Experiments - Year 2

Seeds of cv Nandor were drilled in double rows into a sandy loam to a target density of 100 plants m^{-2}. Beds were top-watered until 56 days after drilling. Thereafter, they were irrigated from seep hose laid between pairs of rows. Root water status (measured as mean soil water potential, Ψ_{soil}), was manipulated using three different irrigation regimes:

i) early watering (56-97 days after drilling) at 19.6mm per week followed by 4.9mm per week from 98-182 days after drilling,

ii) even watering (56-182 days after drilling) at 9.8mm per week,

iii) late watering: 4.9mm per week from 56-139 days and 19.6 mm per week from 140-182 days after drilling. (see Fig 3 for record of Ψ_{soil}).

Duplicate samples (>50 roots) were hand-dug from each treatment at 06.00 h throughout the experiment.

Experiments - Year 3

Carrots of cv Nairobi and Narman were grown in the field at Wellesbourne. Both varieties were sown on two dates, 7 April 95 and 4 May 95 and harvested on four different occasions for each sowing. Row lengths sufficient to provide at least 100 roots per harvest per variety were removed from the soil. Mean plant densities for harvested areas of sowings 1 and 2 were 92 and 104 plants m^{-2} respectively with

ranges of 72-115 and 75-117 across all samples. These were separated into the following categories: commercially-acceptable, split, fanged, diseased and very small. Total weights and numbers of all categories were recorded. Each of the acceptable roots was weighed and its length and diameter recorded. These were then drop-tested and a random selection of undamaged and damaged roots used for measurement of tensile strength, fracture toughness, water potential, solute potential, turgor potential, dry matter content and phloem to xylem dry matter ratio. For some harvests apoplast volume fraction was also measured. Samples were also frozen in liquid nitrogen and stored at <-40°C for chemical analysis of cell walls.

There was also a commercial scale trial in which soil cultivation (tillage as in Year 1) and irrigation treatments were applied to a crop of cv Nairobi, by W H Knights. Passages of the Cultijector, which was used to loosen soil between rows of plants, were made on two 6-bed strips (treatments B and D) in July, August and September. The July pass was followed by 25mm of irrigation to one of these strips (treatment B), while the second strip (treatment C) received only 8mm. Adjacent uncultivated control beds also received these different irrigation regimes (treatment A, 25mm and treatment D, 8mm). Pressure on availability of irrigation resources during the very dry summer of 1995, did not permit further differential irrigations to be applied after the second and third cultivation treatments. Later in the summer, significant volumes of irrigation water were applied to the whole crop. Hand dug samples were taken on 28 September, 12 October and 2 November 1995. On the first of these dates samples were assessed by Knights for yield and marketable quality. For the latter two, samples were sent to HRI Wellesbourne where root size, marketable quality, physiological and mechanical properties were measured.

The crop was strawed over in November and finally lifted and subjected to full scale commercial processing on 21 January 1996. This delay from the originally planned autumn lift was for commercial reasons. Assessment of samples of "raw feed" to the packing line were made at W H Knights and at Wellesbourne. Commercially-packed crates of carrots, identified by letter only were then sent to Sainsbury's in London and to Wellesbourne. At Sainsbury's the roots were evaluated for skin finish, colour and damage. At Wellesbourne, the proportions of damage and undamaged roots were estimated and physiological and mechanical properties were measured.

METHODS

Mechanical testing

Drop test

As soon as possible after lifting, roots were washed, weighed individually and wrapped in a polythene bag to prevent moisture loss. Each root was then subjected to a drop from a slow-moving conveyor belt (0.145 ms^{-1}) on to a flat concrete base 0.88 m below. The roots were always orientated with their tip first. Sideways twisting as the roots fell from the end of the belt was minimized by the presence of guides set approximately 8 cm apart. This arrangement usually resulted in the roots rotating through 90° and landing lengthways on their sides. The precise orientation at impact was always uncertain, so one could never be sure of the area of root over which the force was dissipated. However, roots never landed "end on" at the tip or shoulder.

Tissue tensile strength

Rectangular test pieces (>20 x 2 x 2mm) were removed from the phloem parenchyma of carrot roots and fixed to card templates with cyanoacrylate "superglue", giving an effective specimen length of 17.5mm. A notch (1mm in depth) was made in the centre of each specimen prior to testing to ensure failure at a consistent position. Specimens were extended at a rate of 1mm min^{-1} until failure. Specimens not failing at the notch were discarded. Strength was calculated as failure force divided by specimen cross-sectional area ($2mm^2$). This test measured strength in the radial longitudinal direction (the fracture plane for harvest splits).

Tissue fracture toughness

Blocks of tissue (measuring 5 x 3 x 5mm) were removed from the phloem parenchyma using parallel-mounted blades. Specimens were positioned with the tissue adjacent to the skin *in vivo* uppermost on the testing stage of an Instron universal testing instrument. Fracture toughness was measured by slowly driving a 30° wedge into a free-standing block of tissue so that it split longitudinally (with respect to its original orientation in the carrot). Initially the wedge cuts into the tissue and the load on the

tissue increases. As it penetrates further the sides are bent outwards. Soon after this point is reached, the crack becomes free-running and flows ahead the wedge tip. The load decreases rapidly and stabilises at a constant level during the free-running phase. (The process is analogous to splitting a log with an axe). Fracture toughness (the energy required to create a new fracture plane) was calculated from this stable part of the force-displacement curve.

Water status

Soil water potential

Duplicate cores of soil were removed from plots at 7 day intervals and relative water content determined after drying samples at 95°C for 72 h. Soil water potential (Ψ_{soil}) for these samples was estimated from a previously-established relationship with relative water content determined by measuring relative water content of soil samples equilibrated at constant pressure.

Tissue water potential

For roots less than 10g lateral roots were removed and 10mm sections isolated. For roots heavier than 10g, discs (2-3mm in thickness) were removed from the outer phloem parenchyma using a 7mm diameter cork borer.

Tissue was placed in the sample wells of psychrometer chambers and left for 3h before water potential (Ψ_{tissue}) was measured.

Tissue solute potential

The same tissue as that used for Ψ_{tissue} measurements were disrupted by freeze-thawing and sap obtained by centrifugation. Solute potential of the sap was measured in duplicate using a vapour pressure osmometer calibrated with sodium chloride standards.

Tissue turgor potential

Turgor potential was estimated as the difference between tissue water and solute potentials of root tissue.

Tissue structure

Apoplast volume

The apoplast consists of cell walls and air spaces. Since carrot tissue has few air spaces (porosity <1%), measuring the size of apoplastic volume is a reliable method for estimating cell wall volume fraction.

Discs of phloem parenchyma (7mm diameter, 1mm thick) were cut and incubated in a solution of radioactively labelled mannitol. This compound diffuses into the apoplast but does not cross cell membranes. After > 2 h discs were removed, rinsed in 1mM calcium chloride to remove excess mannitol, placed in scintillant and counted in triplicate using a scintillation counter.

Apoplast volume fraction was calculated as:

$$(\text{counts min}^{-1}_{\text{disc}} / \text{weight}_{\text{disc}}) / \text{counts min}^{-1}_{\text{incubating solution}}.$$

Cell size measurements

Pieces of tissue were removed from the outer phloem parenchyma and glued on to stubs. These were frozen in liquid nitrogen, coated with gold and viewed using a scanning electron microscope. Cell diameter was determined in triplicate for each specimen.

Root colour

In 1993, colour was measured using a Hunter reflectance colorimeter, which gives three variables for each specimen:

'L': lightness (0 = black, 100 = white),

'a': red (positive values) to green (negative values),

'b': yellow (positive values) to blue (negative values).

Four equidistant readings were taken from each carrot (*ca.* 50mm from the crown and avoiding the lateral root traces).

In 1995, a Minolta hand-held reflectance spectrophotometer was used to provide colour data based on the same 'L-a-b' system of colour definition. Measurements made on samples which had experienced cool-chain handling were separated into those from "silvered" and "non-silvered" areas of roots.

GLOSSARY

Apoplast:	the region outside the membrane of the living cell (i.e. cell walls and air spaces
Failure stress:	stress required to break a specimen.
Phloem parenchyma	relatively undifferentiated plant cells found in tissue which includes the food-conducting vessels (phloem). In carrots, it is in the root sheath and is mostly used for storage of reserves.
Solute potential:	a measurement of the water present in a solution of plant sap
Stress:	force or load per unit area
Strength:	measured as the load or stress required to break a specimen
Tensile strength:	stress required to break a specimen by pulling
Toughness:	measurement of resistance to fracture. A material which is very brittle is not tough, but can be strong.
Turgor potential:	a measurement of internal pressure on the cell wall, exerted by a cell's ability to attract water. It is the difference between water and solute potentials.
Water status:	collective term for water potential, solute potential and turgor potential.
Water potential:	a measurement of the water present in living plant tissue, relative to an open water surface
Xylem parenchyma:	relatively undifferentiated plant cells found in tissue which includes the water-conducting vessels (xylem). In carrots it is in the root core and is mostly used for storage of reserves.

ACKNOWLEDGEMENTS

This project was co-funded by the Department of Trade and Industry as part of the Agro-Food Quality LINK scheme and comprised a consortium with the Centre for Biomimetics (University of Reading), Marks & Spencer plc and J Sainsbury plc. Assistance from Dr M Groom of W H Knights, C. Pillinger (Liverpool University sandwich student at HRI) is also gratefully acknowledged.

The project was lead during its first two years by Dr Anthony McGarry. Illness prevented him from completing the final year of work and he eventually passed away in February 1995.

PUBLICATIONS

Refereed scientific

McGarry, A. (1994). Cellular basis of tissue toughness in carrot (*Daucus carota* L.) storage roots. Annals of Botany **75**, 157-163

Popular articles

McGarry, A. (1994). Carrot irrigation is a quality issue. The Grower (August 25), 13-14

McGarry, A. (1994). Watered down carrot quality. The Grower (August 18), 35-36

Presentations

McGarry, A. (1993) Mechanical properties of carrots. HDC/ADAS/HRI carrot subject day. ADAS Arthur Rickwood EHF

McGarry, (1993) A mechanical factors involved in carrot splitting. AAB meeting on 'Post-harvest handling of fruit, vegetables and flowers', at the Linnaean Society of London.

Mcgarry, A. (1994) Quality and Structure. Keynote address at EC workshop on 'Mechanical properties of horticultural produce', Brussels,

McGarry, A. (1994) Splitting and carrot quality. ADAS Quality carrot conference.

Hole, C. C. (1994) Cellular basis of tissue strength. AFQ LINK Dissemination Event, 4 May, Reading University.

Hole, C. C. (1995) Factors affecting textural properties and cracking of carrots. AFQ LINK Dissemination Event, "Cell walls and tissue structure: texture and processing of plant materials", 24 November, IFR Reading.

Hole, C. C. (1996). Can carrot splitting be cracked? ADAS/HDC Quality Carrot Conference, 8 February, Kelham Hall, Newark

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McGarry, A. (1993). Effect of water status on carrot (*Daucus carota* L.) fracture properties. Journal of Horticultural Science **68**, 431-437

McGarry, A. (1994). Cellular basis of tissue toughness in carrot (*Daucus carota* L.) storage roots. Annals of Botany **75**, 157-163

Runham, S. R. (1994). Carrots: pre-harvesting treatments to reduce damage during harvesting operations. HDC Research Report on Project FV46

Table I. Effect of soil tillage and irrigation on yield and damage in Liberno carrots (Year 1).

Tillage/irrigation	Fresh root weight (g)	% damaged roots
+/+	128.1 ± 17.7	11.8 ± 6.6
-/+	96.5 ± 12.9	9.2 ± 3.9
+/-	117.8 ± 15.5	16.1 ± 9.2
-/-	114.1 ± 9.4	11.7 ± 4.9

TABLE 2

Effect of irrigation regime on mean root weight and mean marketable root weight of cv Nandor at final harvest (Year 2).

Treatment	Mean root weight, g	Mean marketable root weight, g
Early watering	89.1	83.3
Even watering	49.1	53.1
Late watering	73.8	71.5
lsd (p=0.05)	10.9	9.7

TABLE 3. Effect of irrigation treatment on the fresh weight of storage roots of cv Nandor carrots (treatments as in text; O=observed values, E=expected values).

Root fresh weight, g	Early-watered		Even-watered		Late-watered		Total
	O	E	O	E	O	E	
0 - 40	34	63	156	114	80	93	270
40.1 - 80	46	47	84	85	71	69	201
80.1 - 120	34	24	31	44	39	36	104
120.1 - 160	29	17	15	30	28	25	72
160.1 - 200	12	6	3	12	13	10	28
200.1 +	5	3	3	6	7	5	15
Total	160		292		238		690

X^2 = 73.19, significant at $p < 0.001$ (based upon 10 degrees of freedom)

Table 4. Effect of irrigation treatment on the incidence of growth splitting in cv Nandor carrots (treatments as in text; O=observed values, E=expected values)

	Early-watered		Even-watered		Late-watered		
	O	E	O	E	O	E	Total
Split	32	19.9	43	36.4	11	29.7	86
Not split	128	140.1	249	255.6	227	208.3	604
Total	160		292		238		690

X^2 = 23.11, significant at $p < 0.01$ (based upon 2 degrees of freedom)

Table 5. Effect of storage root fresh weight on the incidence of splitting in cv Nandor carrots (O=observed values, E=expected values) .

Root fresh	Split		Not split		
weight, g	O	E	O	E	Total
0 - 40	9	33.7	261	236.4	270
40.1 - 80	28	25	173	176	201
80.1 - 120	18	13	86	91	104
120.1 - 160	20	9	52	63	72
160.1 - 200	7	3.5	21	24.5	28
200.1 +	4	1.8	11	13.1	15
Total	86		604		690

X^2 = 45.47, significant at $p < 0.001$ (based upon 5 degrees of freedom)

Table 6. Effect of irrigation treatment on storage root colour in cv Nandor carrots (Year 2).

Colour values	Early-watered	Even-watered	Late-watered	lsd (p=0.05) (120 df)
L	42.3	40.9	41.7	1.02
a	9.0	9.2	10.7	0.91
b	15.2	15.4	17.0	0.64

'L' is lightness or the balance between black (0) and white (100)

'a' is red-green balance (where a positive value is more red and negative is more green)

'b' is yellow-blue balance (where a positive value is more yellow and negative is more blue)

Table 7. Dry matter content of tissues and ratio of phloem tissue (sheath) to xylem tissue (core) for roots at different times after sowing (year 3).

Treatment	Dry matter content, %		Phloem/xylem fresh weight ratio
	Phloem tissue	Xylem tissue	
Sowing 1			
178 days			
cv Nairobi	12.4	11.2	0.24
cv Narman	14.2	12.0	0.42
Sowing 2			
158 days			
cv Nairobi	11.4	10.5	
cv Narman	12.8	10.7	
172 days			
cv Nairobi	11.3	10.3	
cv Narman	12.7	11.0	
188 days			
cv Nairobi	10.9	10.3	
cv Narman	12.2	10.5	
lsd ($p<0.05$)	0.91	0.83	0.124

Table 8. Apoplast volume fraction of carrot phloem parenchyma in cvs Narman and Nairobi at various times after sowing (year 3).

Variety	Apoplast volume fraction % at				Variety mean
	144 days	158 days	172 days	188 days	
Narman	10.4	13.2	22.2	17.8	15.9
Nairobi	11.0	9.9	17.4	15.9	13.6
Harvest mean	10.7	11.6	19.8	16.9	
LSD ($p<0.05$):					
variety	1.18				
harvest	1.70				
harvest.variety	2.63				

Table 9. Means of variables of roots from a commercial crop of cv Nairobi, sampled 12 October 1995.

Measured variable	Treatment				lsd p=0.05
	A	B	C	D	
Root fresh weight, g	65.0	58.8	78.4	67.1	12.3
Failure stress, MPa	1.06	0.99	1.09	1.02	0.163
Fracture toughness, Jm^{-2}	415	455	504	504	51.8
Water potential, MPa	-0.63	-0.61	-0.62	-0.63	0.032
Solute potential, MPa	-1.06	-1.05	-1.07	-1.08	0.033
Turgor potential, MPa	0.43	0.44	0.45	0.45	0.035
Xylem dry matter, %	8.6	8.5	8.6	9.0	0.46
Phloem dry matter, %	9.8	9.8	9.9	10.2	0.58

Treatments: A, uncultivated/higher irrigation; B, cultivated/higher irrigation; C, cultivated/lower irrigation; D, uncultivated/lower irrigation

Table 10. Means of variables of roots from a commercial crop of cv Nairobi, sampled 2 November 1995.

Measured variable	Treatment				lsd p=0.05
	A	B	C	D	
Root fresh weight, g	60	81	89	72	12.1
Failure stress, MPa	0.92	1.05	1.01	1.04	0.160
Fracture toughness, Jm^{-2}	623	614	589	607	53.3
Water potential, MPa	-0.58	-0.55	-0.56	-0.58	0.045
Solute potential, MPa	-1.06	-1.05	-1.05	-1.09	0.036
Turgor potential, MPa	0.48	0.49	0.49	0.52	0.055
Xylem dry matter, %	8.3	8.5	8.4	8.3	0.59
Phloem dry matter, %	9.7	9.3	9.9	9.8	0.51

Table 11. Means of variables of roots sampled from a commercial crop of cv Nairobi, after final lifting on 21 January 1996.

Measured variable	Treatment				lsd p=0.05
	A	B	C	D	
Root fresh weight, g	71	65	71	69	8
Failure stress, MPa	1.1	1.1	1.2	1.1	0.13
Fracture toughness, Jm^{-2}	646	602	667	611	64
Water potential, MPa	-0.42	-0.40	-0.39	-0.37	0.072
Solute potential, MPa	-1.01	-0.98	-0.98	-0.99	0.083
Turgor potential, MPa	0.58	0.58	0.59	0.62	0.062
Xylem dry matter, %	8.9	8.3	8.5	8.4	0.51
Phloem dry matter, %	9.6	8.7	8.9	8.8	0.51

Treatments: A, uncultivated/higher irrigation; B, cultivated/higher irrigation; C, cultivated/lower irrigation; D, uncultivated/lower irrigation

Table 12. Effect of cultivation and irrigation on colour of saleable roots from commercial crop of cv Nairobi (Year 3).

Sampling date	Cultivated	Uncultivated	Higher irrigation	Lower irrigation	lsd p=0.05
2/11/95					
L	39.4	39.0	39.2	39.2	0.62
a	13.5	12.5	13.0	13.0	0.72
b	16.7	16.3	16.4	16.6	0.47
21/1/96					
L	39.8	39.9	39.7	40.0	0.85
a	14.6	14.1	14.3	14.4	0.45
b	16.5	16.3	16.2	16.5	0.88

Table 13. Proportions of saleable and damaged roots in raw feed to packing line for commercial crop, 21 January 1996 (Year 3).

Measured variable	Treatment			
	A	B	C	D
Sample weight, kg	20.3	18.2	19.5	19.4
Number of roots	262	286	287	336
Mean fresh weight, g	77.5	63.8	67.9	57.6
Proportion*				
saleable, %	43.1	51.4	41.8	36.9
split, %	2.7	1.8	3.5	2.7
breaks, %	6.1	7.3	11.9	5.4

* remainder not saleable for other reasons, e.g. mis-shaped, diseased

Table 14. Proportion of roots of packed, saleable product damaged in transit and the susceptibility to damage in drop test of undamaged roots (Year 3).

Measured variable	Treatment			
	A	B	C	D
Mean fresh weight, g	68.8	67.2	72.4	71.5
Damage				
in transit %	18	14	20	10
in drop test %	22	21	21	16

Fig. 1. Sensitivity of failure stress of carrot root phloem parenchyma to relative notch size (year 1).

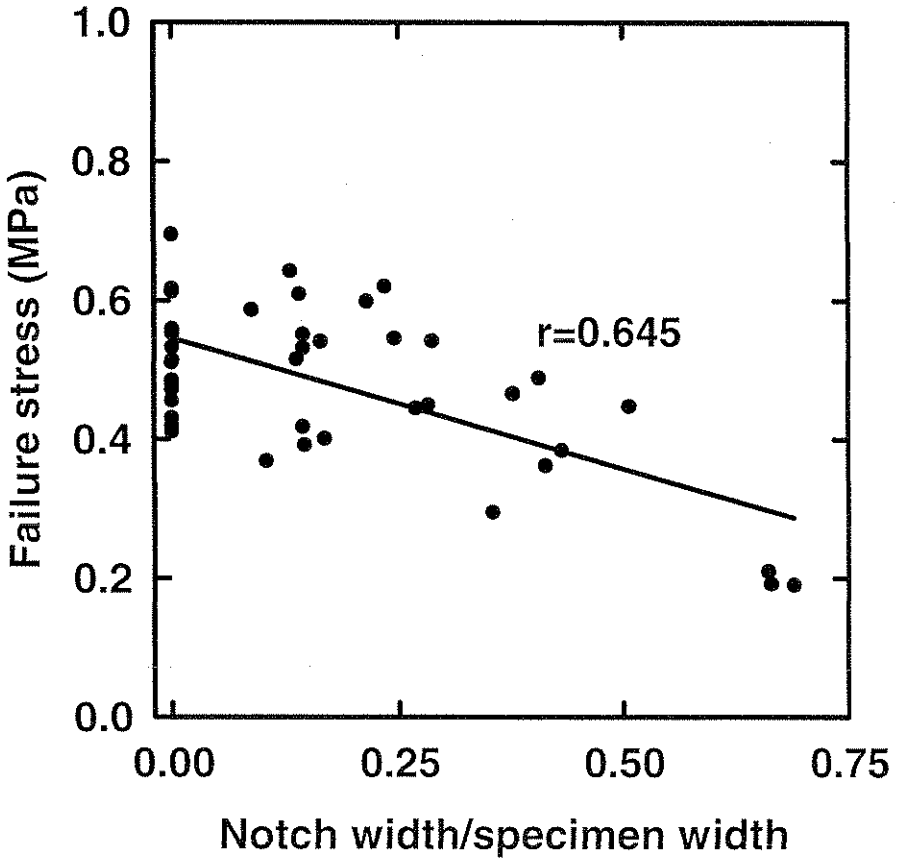


Fig. 2. Changes in water status of carrot root phloem parenchyma during development (cv. Narman, year 1). Error bars are ±standard deviation.

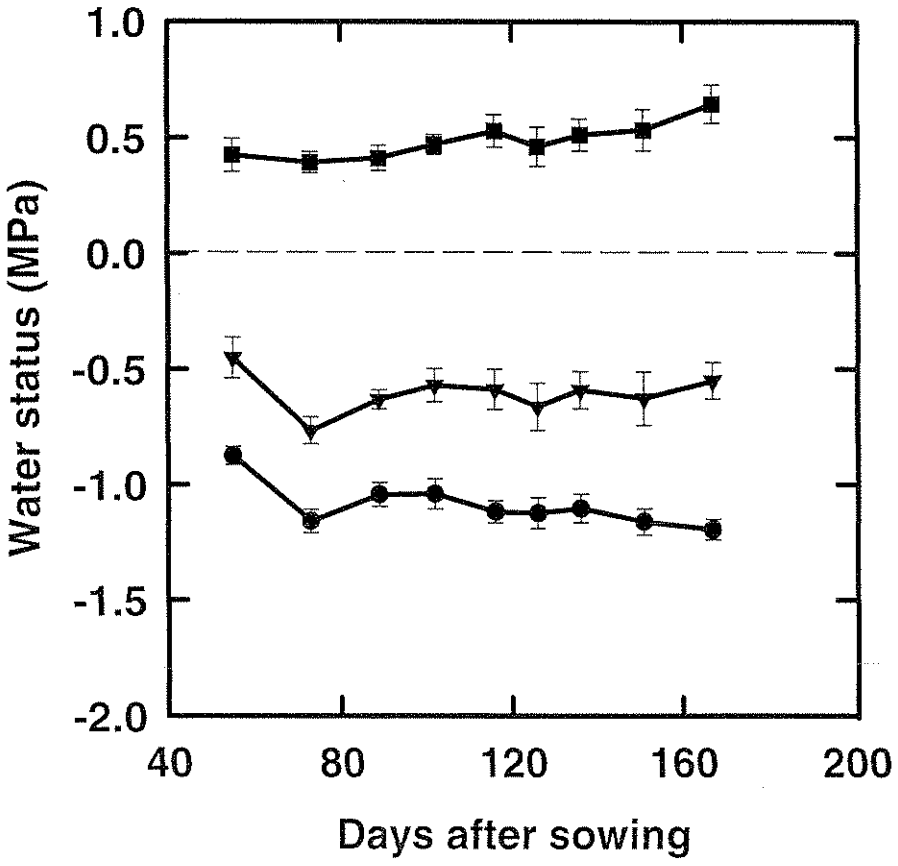


Fig. 3. Soil water status of different irrigation regimes (year 2).

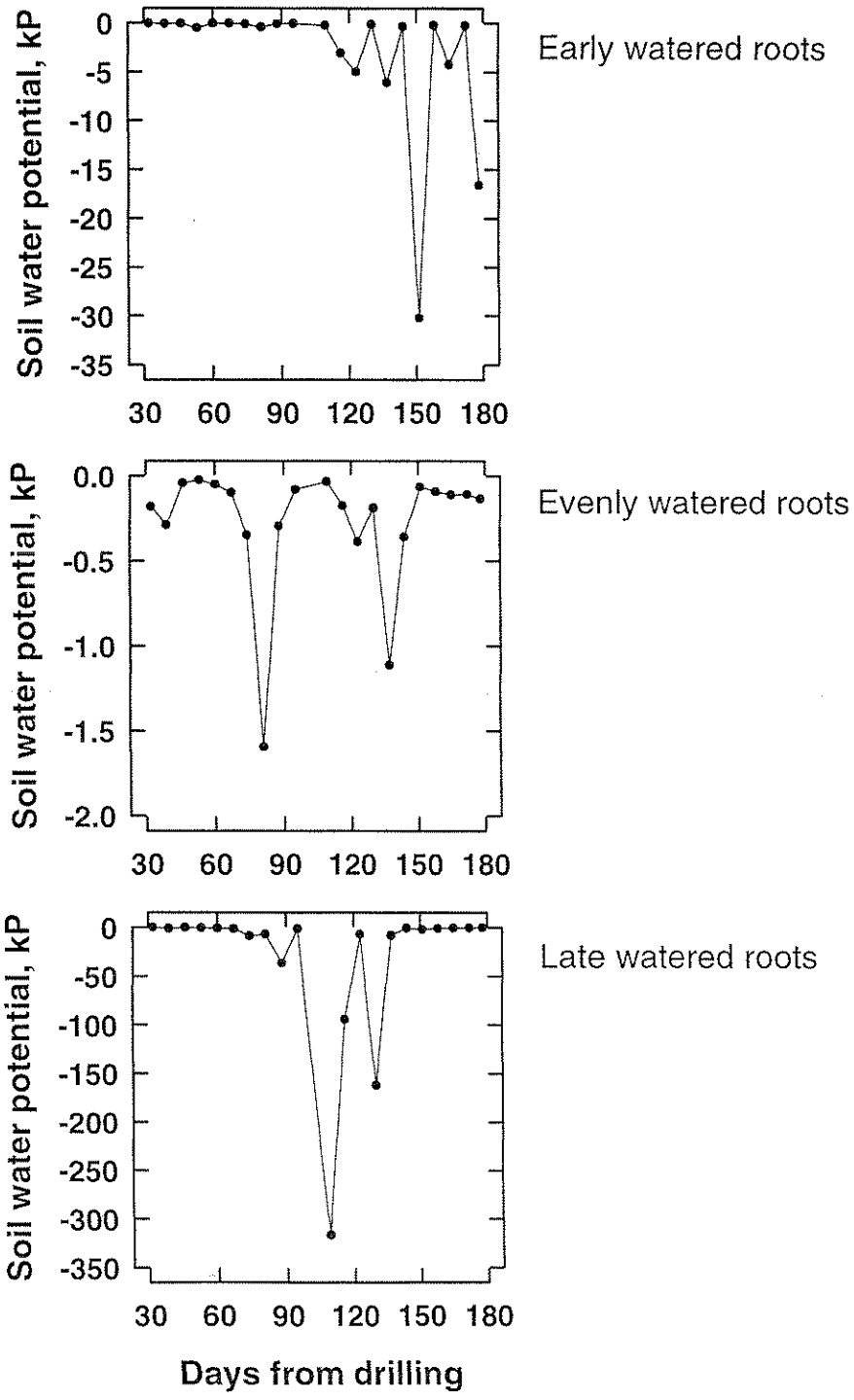


Fig. 4. Changes in root fresh weight with time for carrot roots (cv. Nandor) from different irrigation regimes (year 2): ● = early-watered, ■ = evenly-watered, ▲ = late watered.

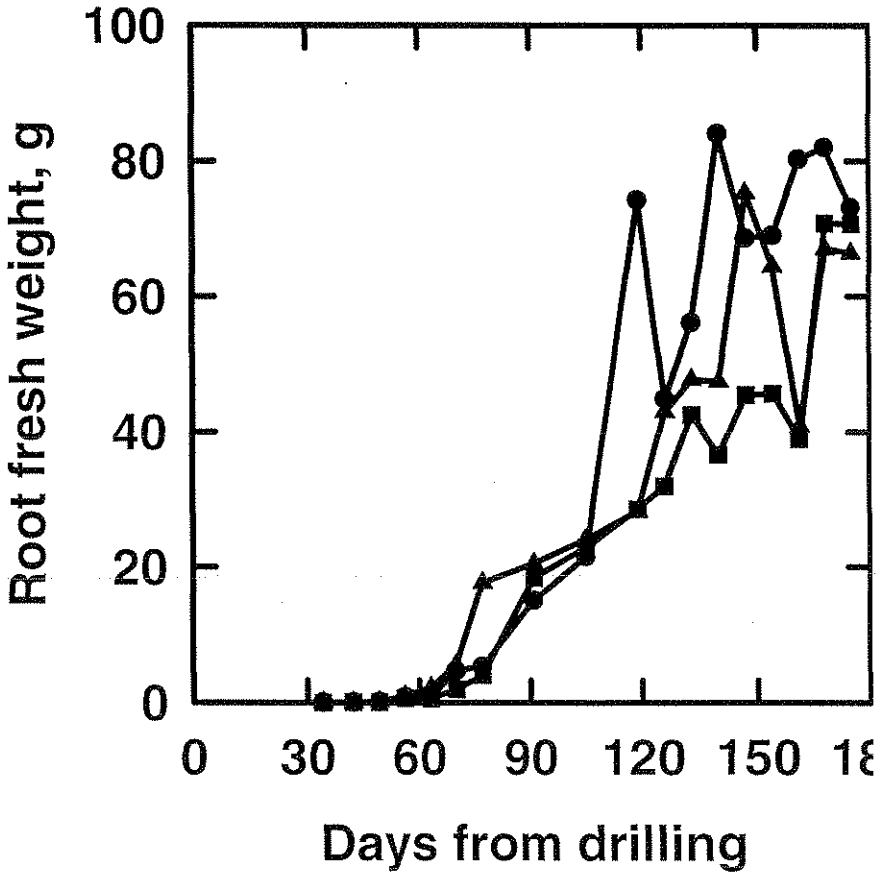


Fig. 5. Incidence of root splitting with time for cv. Nandor grown in different irrigation regimes (year2):

● = early-watered, ■ = evenly-watered, ▲ = late watered.

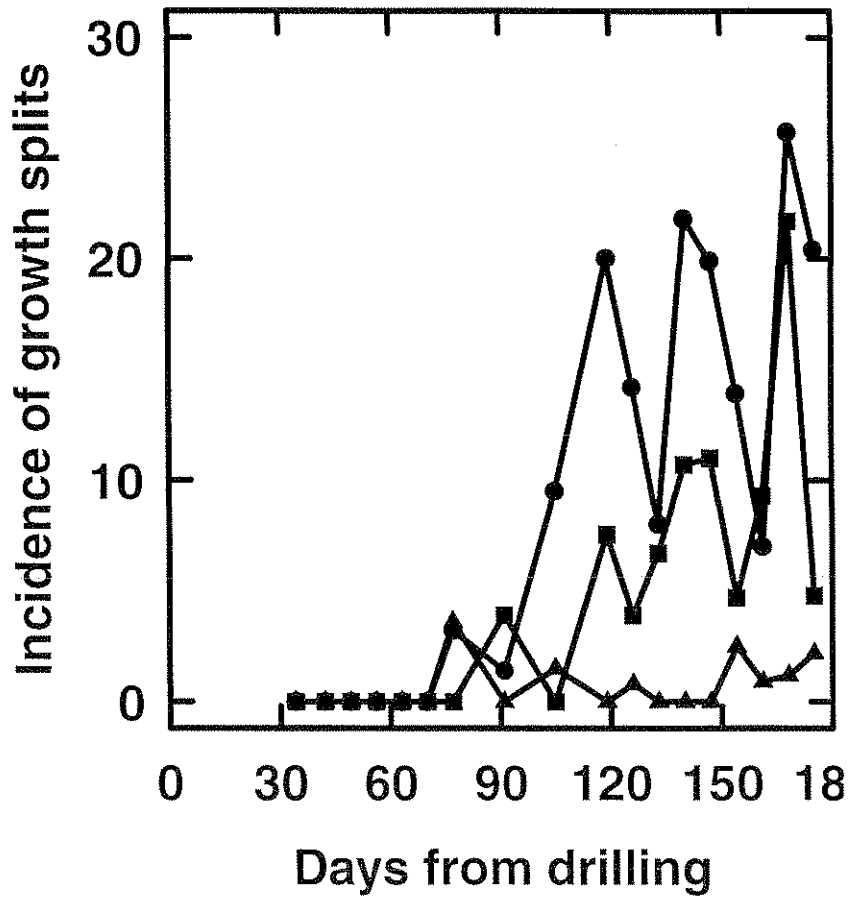


Fig. 6. Frequency distribution of root fresh weight with root age and irrigation treatment for cv. Nandor (year 2).

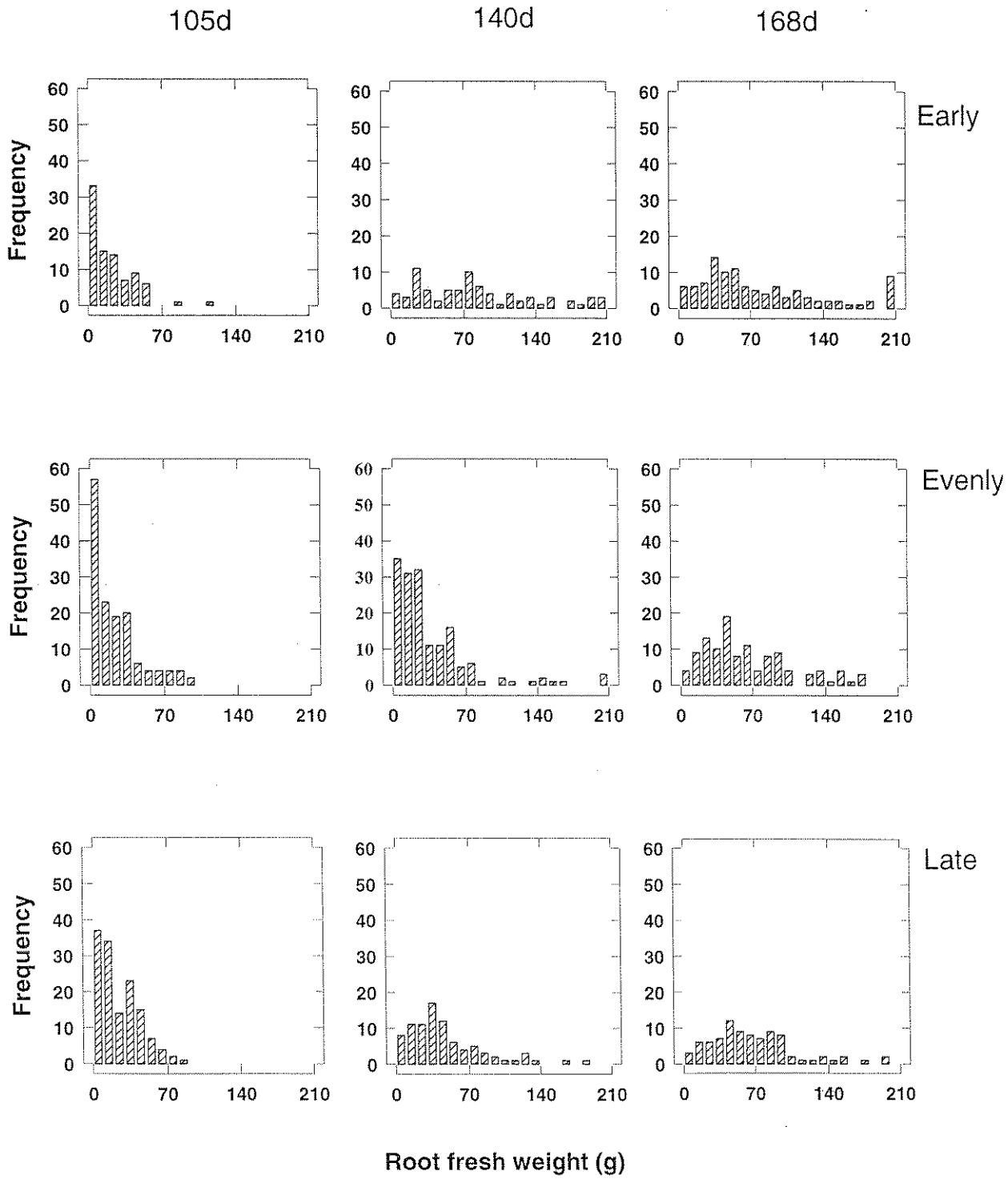


Fig. 7. Changes in water potential (———) and solute potential (- - - - - -) of carrot roots (cv. Nandor) with root age and irrigation treatment (year 2):

●,○ = early-watered, ■,□ = evenly-watered, ▲,△ = late watered. Error bar is least significant difference (lsd) at p=0.05.

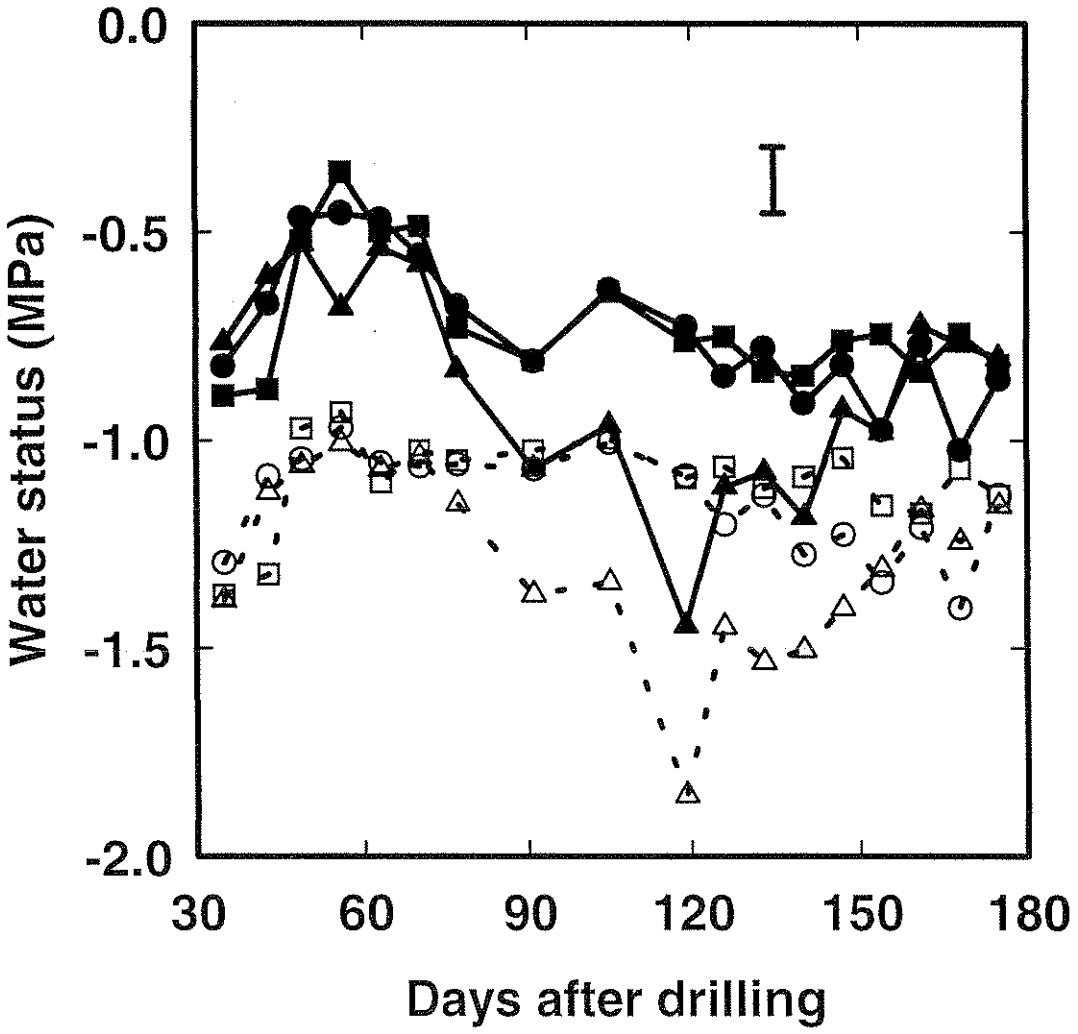


Fig. 8. Changes in turgor potential of carrot roots (cv. Nandor) with root age and irrigation treatment (year 2): ● = early-watered, ■ = evenly-watered, ▲ = late watered. Error bar is lsd at p=0.05.

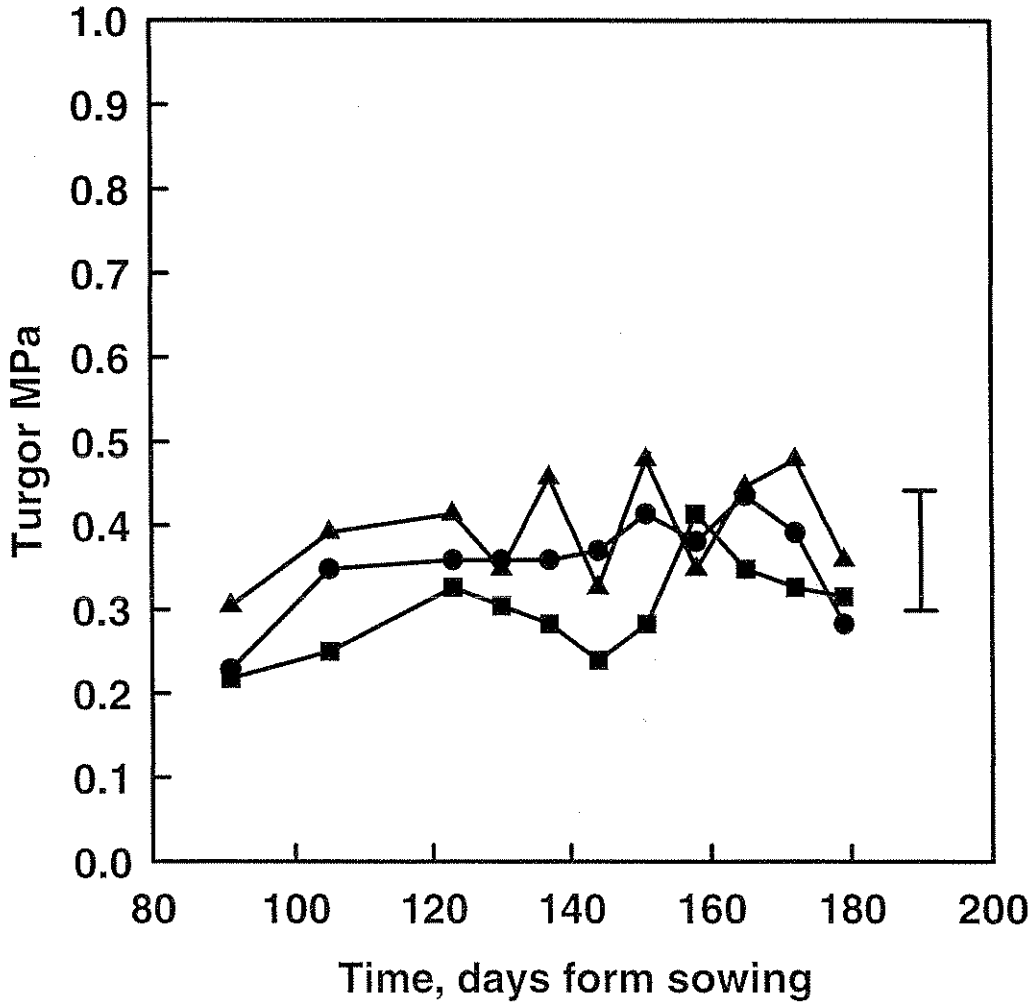


Fig. 9. Relationship between fracture toughness and root water potential in roots (cv. Nandor) lifted 119 days (●, y=274+-292x, r^2=0.78, p<0.01) and 161 days (O, y=265+-334x, r^2=0.62, p<0.01) after drilling (year 2).

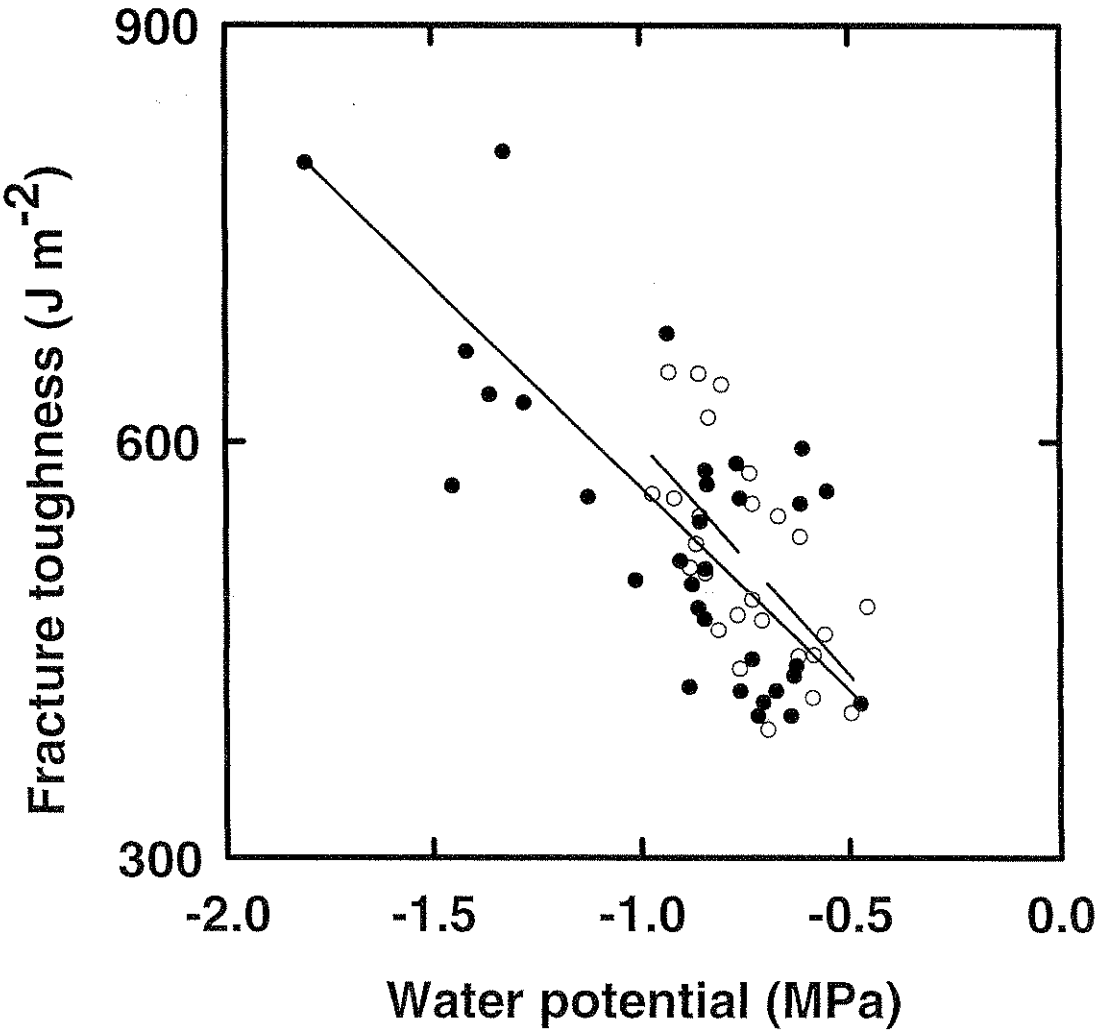


Fig. 10. Changes in fracture toughness of carrot roots (cv. Nandor) with root age and irrigation treatment (year 2): ● = early-watered, ■ = evenly-watered, ▲ = late watered. Error bar is lsd at p=0.05.

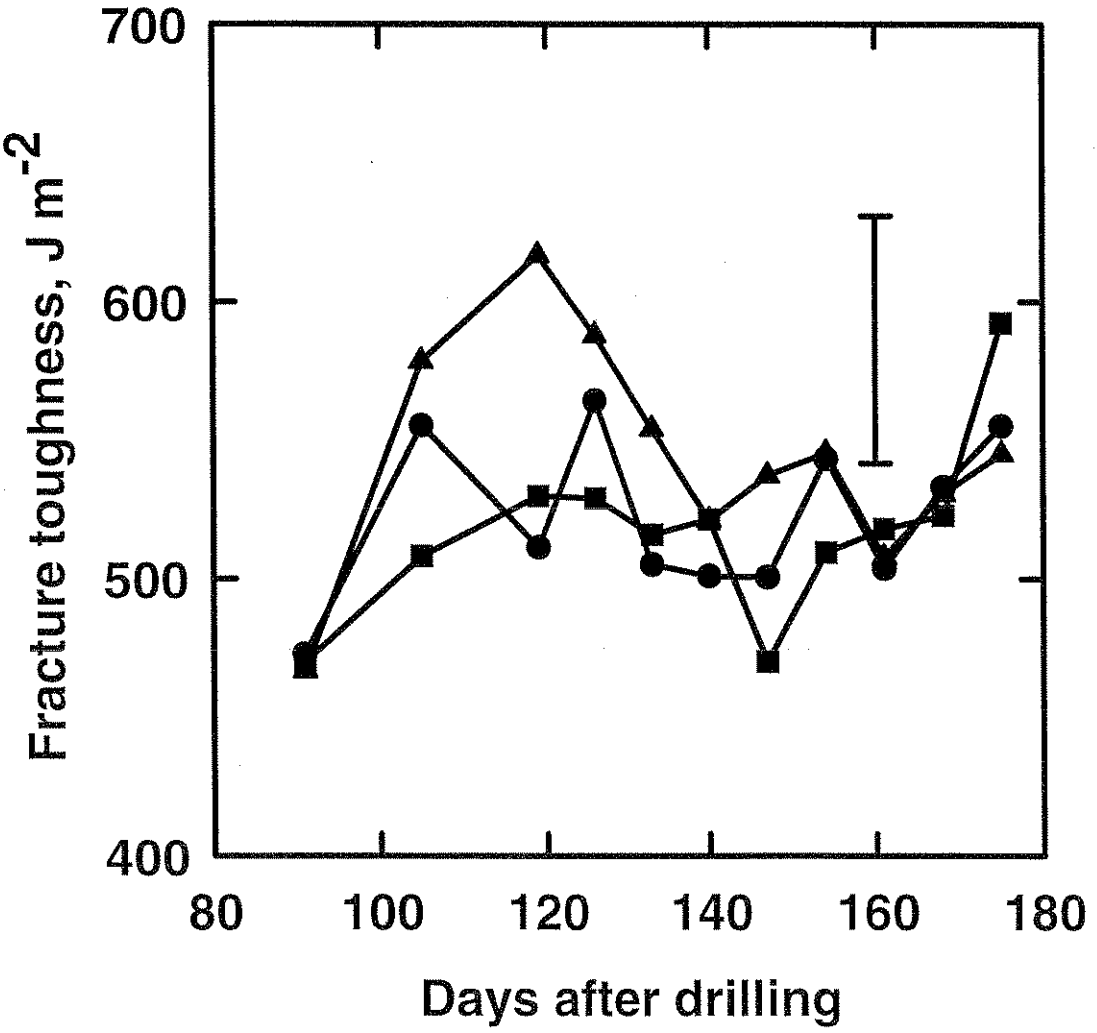


Fig. 11. Relationship between mean fracture toughness and mean root water and turgor potentials (cv. Nandor) for different irrigation regimes and at different times after sowing (year 2): ● = early-watered, ■ = evenly-watered, ▲ = late watered. [Values for turgor potential are all positive.]

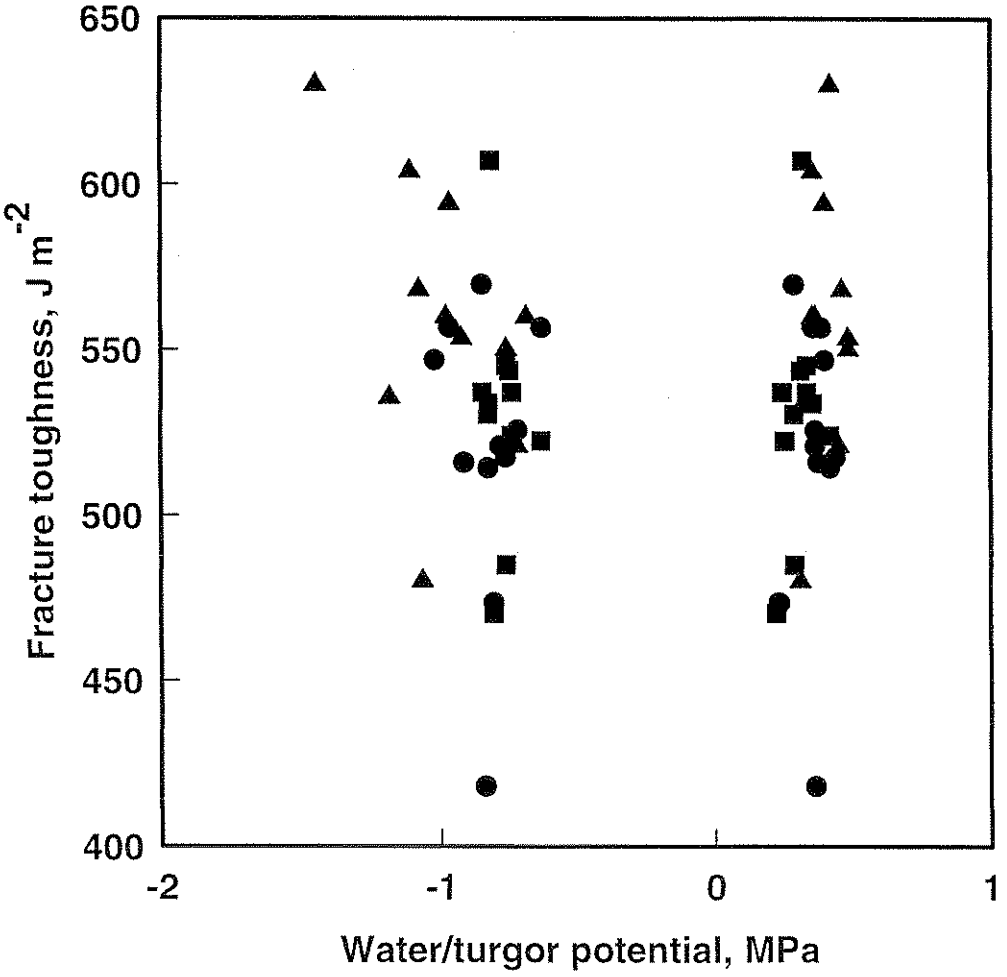


Fig. 12. Changes in tensile strength (failure stress) of carrot roots (cv. Nandor) with root age and irrigation treatment (year 2): ● = early-watered, ■ = evenly-watered, ▲ = late watered. Error bar is lsd at p=0.05.

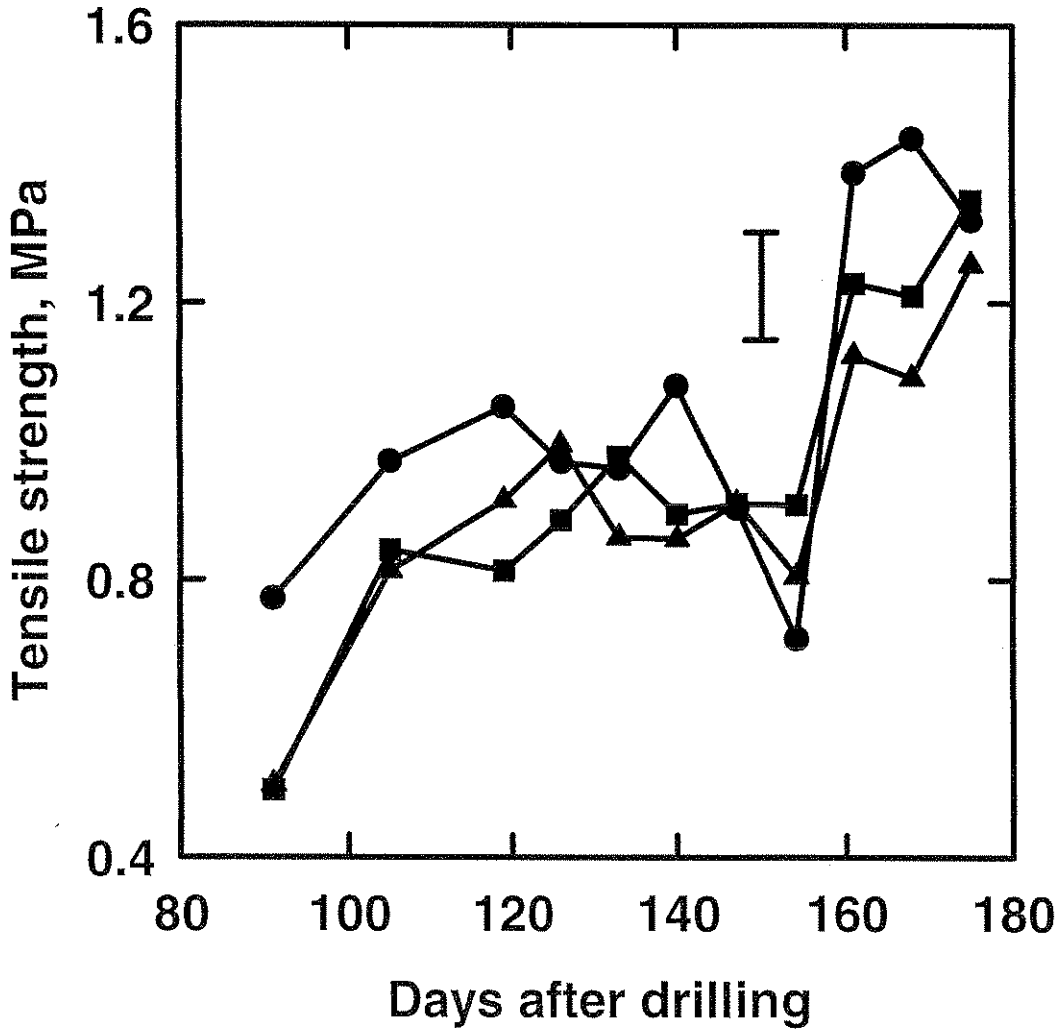


Fig. 13. Changes in cell diameter of carrot storage roots (cv. Nandor) with age and irrigation treatment (year 2): ● = early-watered, ■ = evenly-watered, ▲ = late watered. Error bar is lsd at p=0.05.

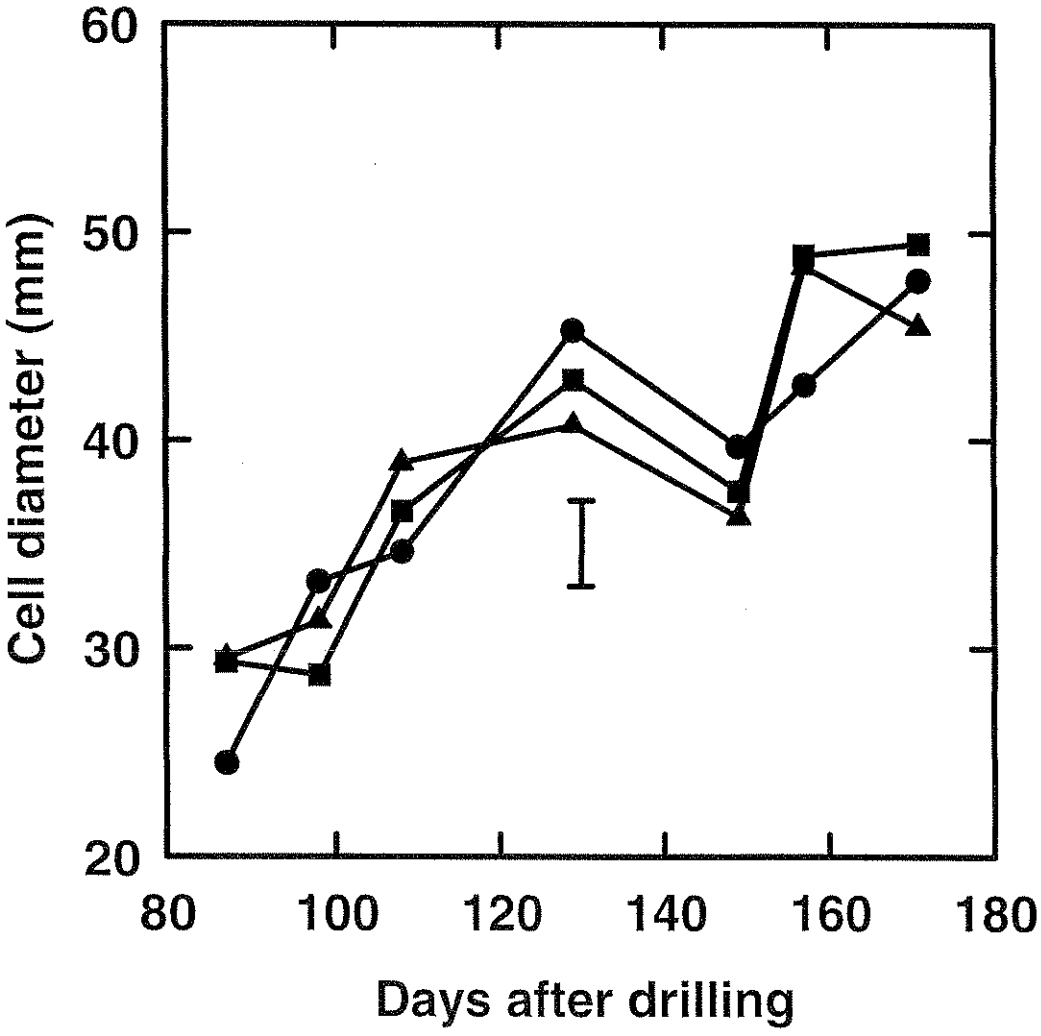


Fig. 14. Changes in apoplast volume fraction (cell wall fraction) of carrot storage roots (cv. Nandor) with age and irrigation treatment (year 2): ● = early-watered, ■ = evenly-watered, ▲ = late watered. Error bar is lsd at p=0.05.

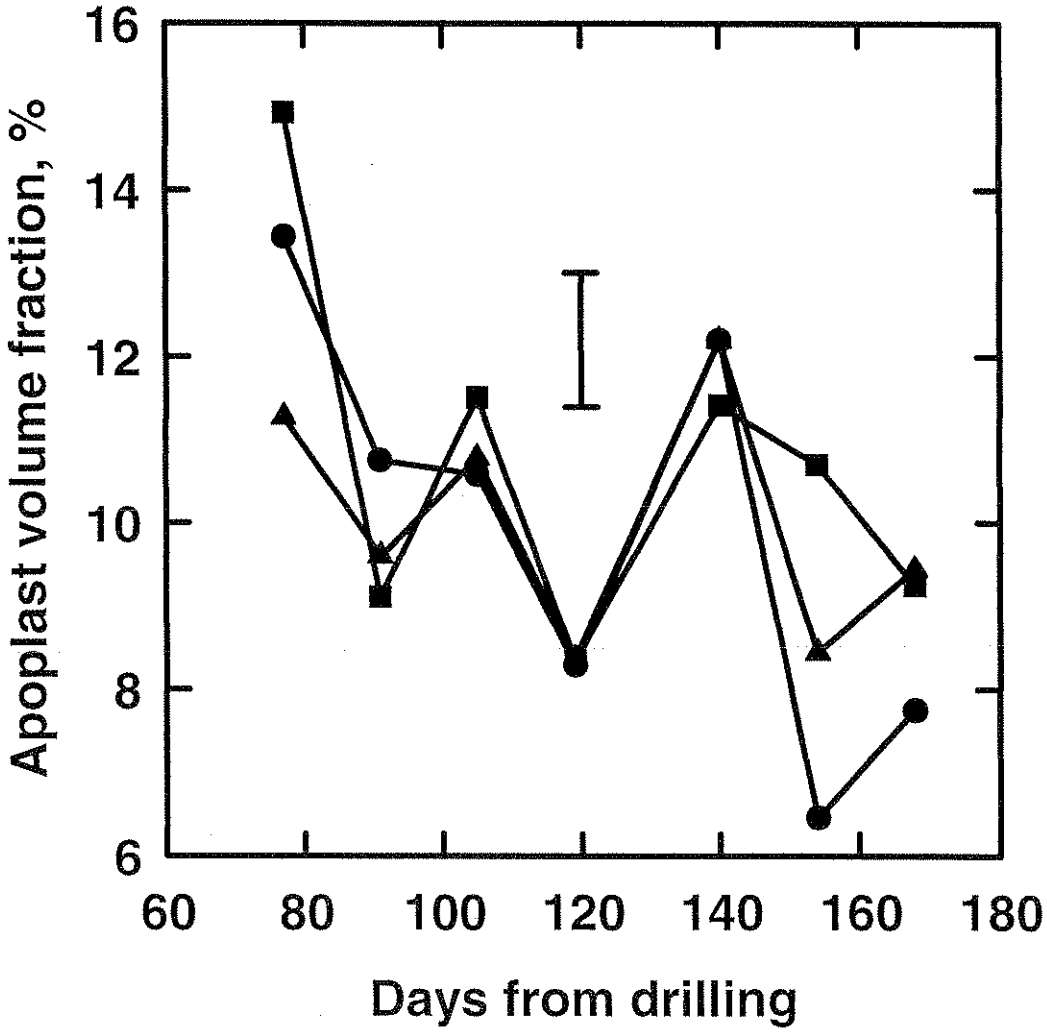


Fig. 15. Changes in tensile strength (failure stress) with time from sowing for roots of cvs Nairobi (●,○) and Narman (■,□) sown on different dates (●,■ = 7 April, 1995; ○,□ = 4 May 1995, year 3). Error bar is lsd at p=0.05.

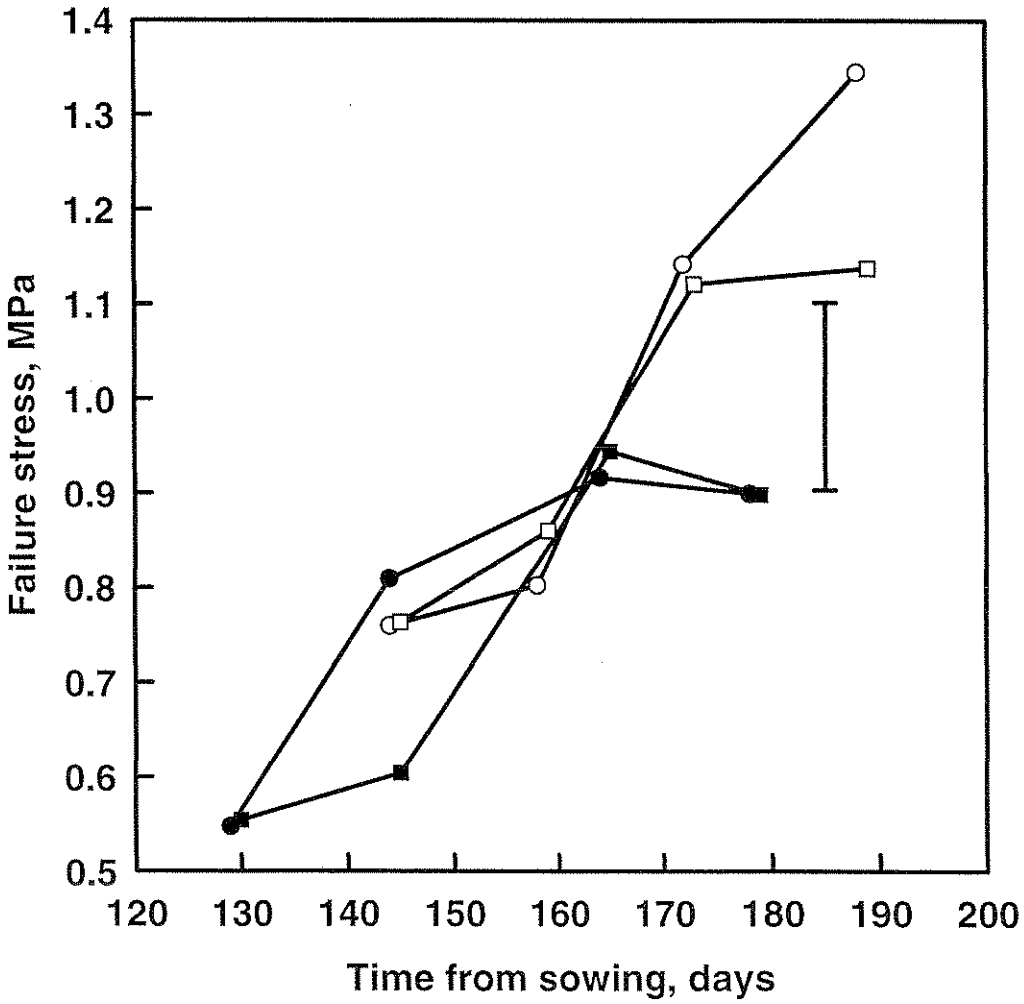


Fig. 16. Changes in fracture toughness with time from sowing for roots of cvs Nairobi (●,○) and Narman (■,□) sown on different dates (●,■ = 7 April, 1995; ○,□ = 4 May 1995, year 3). Error bar is lsd at p=0.05.

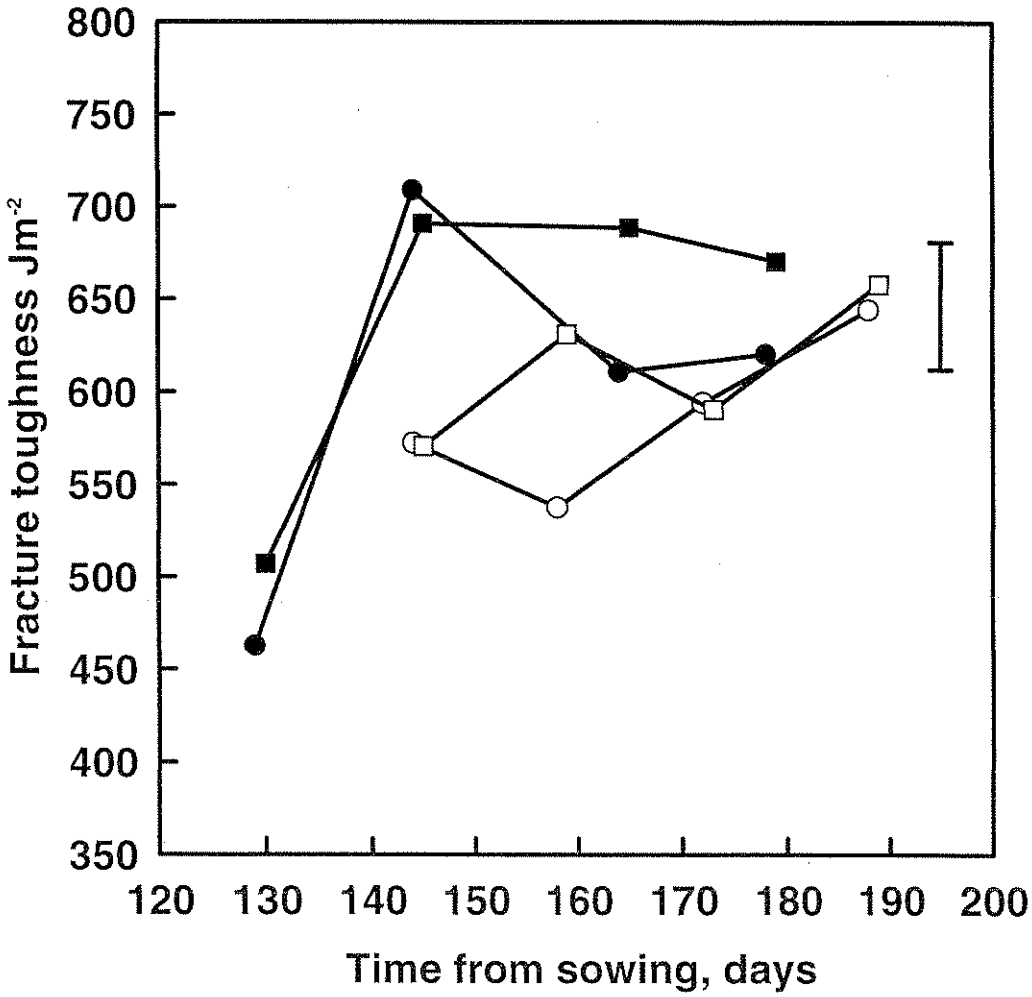
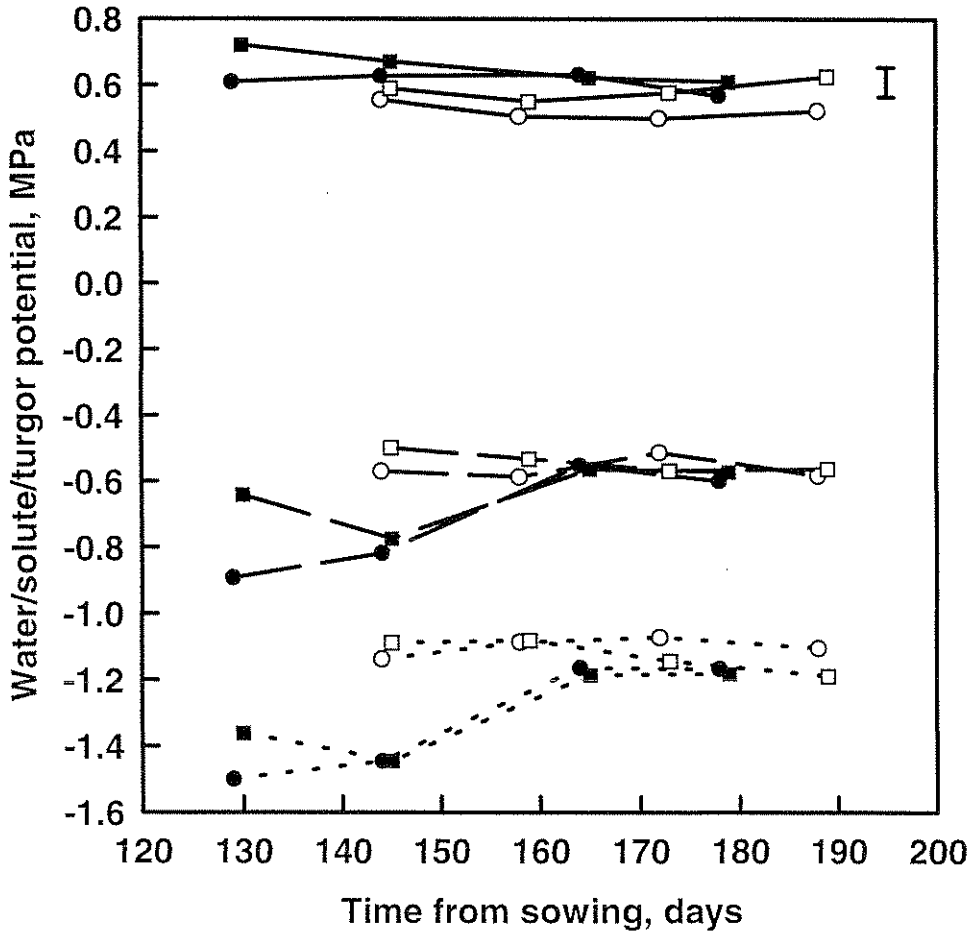


Fig. 17. Changes in water (—— ——), solute (- - - - - -) and turgor (————) potentials with time from sowing for roots of cvs Nairobi (●,○) and Narman (■,□) sown on different dates (●,■ = 7 April, 1995; ○,□ = 4 May 1995, year 3). Error bar is lsd at p=0.05.



Note: water potential and solute potential were analysed as log(0-x), lsd's are not possible for these plots. Transformed means and errors are as follows:

Water potential:

	Harvest / Sowing	1	2	3	4	lsd, p=0.05
Nairobi	1	-0.126	-0.224	-0.646	-0.514	
	2	-0.567	-0.546	-0.563	-0.546	
Narman	1	-0.474	-0.269	-0.581	-0.564	
	2	-0.707	-0.636	-0.575	-0.593	0.088

Water potential:

	Harvest / Sowing	1	2	3	4	lsd, p=0.05
Nairobi	1	0.403	0.366	0.149	0.154	
	2	0.126	0.823	0.068	0.099	
Narman	1	0.305	0.364	0.168	0.165	
	2	0.082	0.077	0.133	0.171	0.053

Contract between HRI and the University of Reading (hereinafter called the "Contractors") and the Horticultural Development Council (hereinafter called the "Council") for a research/development project.

PROPOSAL

1. TITLE OF PROJECT **Contract No: FV/46a**

MANIPULATION OF ROOT MOISTURE CONTENT TO REDUCE CARROT DAMAGE (SPLITTING, BREAKAGE)

2. BACKGROUND AND COMMERCIAL OBJECTIVE

Splitting (longitudinal cracking) in carrots (a major vegetable crop in this country having an annual farm gate value >£50 million, with the UK being one of the largest producers worldwide) is a serious problem with between 15 and 30% of the crop affected during particular seasons.

There is a clear need to establish the relationship between carrot water relations and root fracture properties with a view to devising methods of reducing splitting damage in this major field vegetable which currently costs the industry *ca.* £6-12 million annually (figure based on farm gate prices). Long term goals would be to develop new (or modified) growing methods which reduce susceptibility to spontaneous splitting and improved lifting and handling procedures based upon a better understanding of the relationship between carrot fracture properties, tissue composition, cell wall thickness/chemistry and water relations and how these are affected by agronomy and genotype. Findings from such work could indicate suitable selection criteria for breeders to use as a starting point in programmes aimed at producing lines of split-resistant carrots and may help define those conditions which predispose carrots to splitting. Agronomic and physiological data from this work would be accessible to HDC levy payers via newsletters, reports and meetings; the findings will also be made available to breeders. Before such recommendations can be implemented it would be necessary to verify that any agronomic manipulation did not compromise efficient production practice.

3. POTENTIAL FINANCIAL BENEFIT TO THE INDUSTRY

Since the carrot industry is extremely competitive any findings indicating improvements in agronomic and/or harvesting techniques would be rapidly taken up by UK growers, with the result that the overall incidence of splitting would decline, crop quality would improve, reducing the need for imports (which currently account for *ca.* 6% of UK consumption), and may possibly allow surplus roots to be exported. In addition, such knowledge should enable plant breeders to more efficiently identify and select promising genotypes for inclusion in breeding programmes. Ultimately this may lead to the identification of the genetic basis of splitting damage and its

manipulation by molecular biological techniques.

4. SCIENTIFIC/TECHNICAL TARGET OF THE WORK

The incidence of splitting in carrots has long been recognised as a serious problem but there has been virtually no attempt at examining the underlying cause of this disorder. Part of the reason for this has been the tendency of too many researchers to tackle mechanical problems via the most convenient technique, not the one most appropriate for examining any given problem (Dickson, 1966; Millington, 1986), and the neglect of the role of plant water relations. By combining rigorous mechanical testing (based upon sound engineering principles) with accurate measurements of water relations the precise relationship between these two sets of parameters can be established. Whilst there is every likelihood of successfully establishing the cause of carrot splitting (preliminary evidence suggesting the direction of the probable success), achieving a practical solution to this problem may prove to be more difficult. For instance, if cracking is related to cell size, it may prove difficult to consistently produce carrots composed of small cells by simple agronomic manipulation within the range of conditions which are commercially acceptable. Although it is likely to be relatively straightforward to draw up recommendations, based on data from fracture tests, for reducing the levels of splitting incurred during both conventional lifting and handling procedures (for instance, recommending minimum drop heights in the packhouse based upon impact tests on whole carrots), identifying suitable selection criteria based upon measurements of tissue fracture toughness, structure and chemistry might prove more challenging.

5. CLOSELY RELATED WORK COMPLETED OR IN PROGRESS

To date attempts to combat this disorder have adopted a purely empirical approach, identifying those agronomic factors which appear to be associated with high levels of splitting damage, while failing to tackle the more fundamental issue of the underlying mechanism (see, for instance, Bienz, 1965; Carlton & Peterson, 1963; Dickson, 1966; Knott, 1980; Warne, 1951*ab*). Without such basic information it is impossible to devise reliable agronomic practices aimed at reducing the incidence of splitting. Recent work at Wellesbourne has indicated that root toughness (as measured by various mechanical tests) and resistance to natural splitting can be increased by reducing root turgor immediately prior to harvest.

While carrot tissue has been the subject of various mechanical studies (Millington, 1986; Segerlind, Snobar & Heldman, 1977) these have not been sufficiently rigorous and have failed to consider the influence of plant water relations on carrot fracture properties. Following

discussions with the Biomimetics group at Reading University a number of appropriate mechanical tests have been identified and these include:

(i) Crack opening tests: This involves driving wedges, of varying angles, into free-standing blocks of tissue and measuring tissue fracture toughness (see Khan, 1989).

(ii) Notch-sensitivity measurements: Preliminary work at Wellesbourne has demonstrated that carrot skin is a brittle material (lightly scoring the skin with a blade can cause complete splitting of the carrot as a result of stresses concentrating at the tip of the cut leading to crack growth). Such notch-sensitivity of the skin could account for differences in split-susceptibility between different cultivars.

(iii) Instrumented microtomy: Atkins & Vincent (1984) have described a technique for measuring carrot fracture toughness during sectioning by means of a rotary microtome linked to a force transducer and have related this to root "turgidity/flaccidity" (*sic*). Such a technique could be used at Reading but it is more probable that a similar instrumented microtome will be constructed at Wellesbourne (with the assistance of the Centre for Biomimetics, University of Reading).

Since carrot toughness appears to be intimately linked with root water relations, the above tests will require that both osmotic and water potential measurements will be made on all specimens (and turgor pressure will be determined by calculation and, on occasion, measured directly by means of the pressure probe).

Work at Wellesbourne has already established that carrots split exclusively by cell wall breakage (as opposed to cell separation), so that root strength must be determined to a considerable degree by the number, distribution and type of cells within the tissue as well as the thickness and chemical composition (in terms of the amount and/or distribution of cellulosic polysaccharide; for method see Stevens & Selvendran, 1984) of individual cell walls. From a knowledge of the cellular basis of tissue strength it may be possible to devise suitable agronomic practices to produce more split-resistant roots (the association of splitting with high levels of soil nitrogen may indicate that during rapid growth cell wall synthesis is impaired, resulting in thinner and/or weaker walls) and to establish appropriate selection criteria for breeders to develop lines of carrots with improved resistance to splitting damage. The work will include an examination of impact damage caused by dropping the product from one piece of equipment to another during grading and packing in an attempt to provide information that will allow packhouse procedures to be tailor-made for handling a highly turgid, brittle product.

6. DESCRIPTION OF THE WORK

The majority of the experimental work will take place at Wellesbourne. Here extensive agronomic experience built up over several decades has, more recently, been coupled with expertise in the field of plant water relations. Equipment already in place to perform this work includes scanning and transmission electron microscopes, light microscopes and microtomes for histological work (for studies of cell packing and cell wall thickness/distribution), several vapour pressure osmometers, multi-chambered psychrometers for water potential determinations along with a pressure probe, an oil-filled microcapillary capable of measuring numerous water relations parameters at single cell resolution. In addition a new Instron Universal Testing Instrument (Table Model 4301) will be purchased to upgrade our existing testing facilities.

The role of the Centre for Biomimetics, University of Reading, will be to offer advice and practical assistance in designing, modifying and performing mechanical tests and interpreting the data these generate. At a later stage data from the proposed work may be made available to the Reading group for use in the development and validation of models of plant tissue strength as affected by cellular structure.

The Horticultural Development Council will represent the interests of the industry, ensuring that results from this work are disseminated to levy payers and that the direction of the work continues to address the needs of the UK carrot industry.

Marks & Spencer have agreed to provide input into studies on spontaneous splitting during supermarket "shelf-life".

Milestones

Year 1

(i) Establish relationship between tissue fracture toughness and carrot water relations.

(ii) Establish the influence of root water relations on the notch-sensitivity of carrot tissue.

(iii) Initiate studies on differences in tissue composition (cell packing, wall thickness/orientation and chemistry) between split-resistant and -susceptible cultivars.

Years 2 & 3

(i) Determine resistance to impact damage (splitting) in various cultivars at a range of turgors.

(ii) Continue to examine differences in tissue composition between different cultivars grown under different agronomic regimes and irrigation programmes.

(iii) Determine differences in cell wall chemistry in various cultivars grown under different conditions. Examine the relationship between cell packing, cell wall thickness/composition, fracture toughness and root water relations.

(iv) Confirm the relationship between root fracture toughness and tissue water relations under a range of commercial situations.

(v) Determine performance of modified product under commercial handling procedures and in shelf-life studies.

7. COMMENCEMENT DATE AND DURATION

Start date 1.4.92; duration 3 years.

8. STAFF RESPONSIBILITIES

Project leader: would be Dr A McGarry, Annual Crops Department, HRI-Wellesbourne.

9. LOCATION

HRI-Wellesbourne with inputs from Reading University and Marks & Spencer.

Contract No: FV/46a

TERMS AND CONDITIONS

The Council's standard terms and conditions of contract shall apply.

Signed for the Contractor(s)

Signature.....

Position.....

Date.....

Signed for the Contractor(s)

Signature.....

Position.....

Date.....

Signed for the Council

Signature.....

Position.....CHIEF EXECUTIVE

Date.....