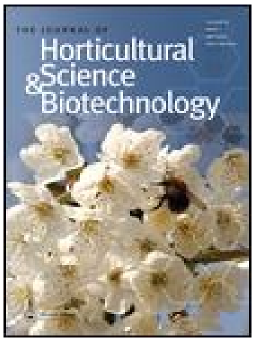

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Influence of preharvest water stress on postharvest moisture loss of carrots (*Daucus carota* L.)

By S. I. SHIBAIRO[1], M. K. UPADHYAYA[1*]; and P. M. A. TOIVONEN[2]
[1]Department of Plant Science, University of British Columbia, Vancouver, B.C. V6T 1Z4, Canada
[2]Summerland Research Centre, Agriculture and Agri-Food Canada, Summerland, B.C. V0H 1Z0, Canada
(e-mail: upadh@unixg.ubc.ca)

SUMMARY

To understand the relationship between preharvest water stress and postharvest moisture loss, carrot cvs Eagle and Paramount were grown in muck soil in 6 l pots (eight carrots per pot) in a greenhouse at the University of British Columbia. The plants were watered to field capacity every second day for 5.5 months prior to receiving 100, 75, 50 and 25% field capacity water stress treatments (for 4.5 weeks), henceforth referred to as low, medium, high and severe water stress respectively. Postharvest moisture loss of carrots stored at 13°C and 32% relative humidity was monitored every second day for three weeks. The percent moisture loss was low in the low water stressed, and high in the severely water stressed carrots of both cultivars. Root crown diameter, weight, and water and osmotic potentials decreased, whereas specific surface area and relative solute leakage increased with increasing preharvest water stress. The results show that carrots adjust to water stress by lowering water and osmotic potentials. Root water potential, followed by relative solute leakage, were the variables which accounted for most of the variation in moisture loss. It is suggested that preharvest water stress lowers membrane integrity of carrot roots, and this may enhance moisture loss during storage.

Preservation of carrot freshness after harvest depends on storage conditions, as well as on structural and physiological characteristics of roots (Fritz and Weichmann, 1979; van den Berg, 1981). Increased moisture loss and respiration results in weight loss of carrots during storage, leading to wilting, loss of colour, and increased susceptibility to infection.

Low-temperature storage has become a common practice to reduce weight loss and maintain quality of carrots. Washing and hydrocooling with a fungicide in the water at 4–7°C for 2–3 min after harvest (Punja and Gaye, 1993), and storage at a constant temperature just above 0°C and humidity approaching saturation (Stoll and Weichmann, 1987; Apeland and Hoftun, 1974) are recommended to reduce moisture loss from carrots.

Root size and shape, structure of evaporating surfaces (Benjamin and Sutherland, 1989; Kays, 1991; Wills *et al.*, 1981), and tissue water potential, which contributes to the driving force for water movement in and out of living cells (Salisbury and Ross, 1991), can all affect postharvest weight loss in carrots. Plant size and structure are greatly affected by the soil water status (Stanhill, 1977). Soil moisture stress reduces leaf water potential which in turn may reduce transpiration (Kramer, 1983). Plants may adjust to mild soil water deficit by lowering their osmotic potential, thereby allowing water absorption when transpiration rates are low (Kramer, 1983; Chapman and Augé, 1994). Whether preharvest water stress influences postharvest moisture loss in carrots is not known. This information is essential to facilitate development of an irrigation regime to enhance the shelf life of fresh carrots. The objectives of this study were to determine: (1) the influence of preharvest water stress on postharvest moisture loss from carrots and (2) the physical and physiological basis of any such influence.

MATERIALS AND METHODS

Seeds of carrot (*Daucus carota* L.) cvs Eagle (a 'Berlicum' × 'Nantes' hybrid, Stokes Seed Ltd., St Catharines, Ontario) and Paramount (Asgrow Seed Co., Newmarket, Ontario) were sown in muck soil (eight seeds in 4 kg of soil per 6 l pot) between May and October (in 1994) and January and July (in 1995) in a greenhouse at the University of British Columbia. 'Osmocote' (14:14:14 N:P:K, Grace Sierra, Milpitas, CA), a controlled-release fertilizer, was added to the soil (3 g kg^{-1} soil) before planting. Carrots were grown in pots in a greenhouse to facilitate preharvest soil moisture stress treatments.

Before seeding, the soil was flooded with water and allowed to drain overnight. The amount of water held by soil at field capacity was calculated as the difference between the weight of soil plus water at field capacity (4.9 kg) and the oven-dried weight

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*To whom correspondence should be addressed.

(105°C for 48 h) of the soil (3.2 kg). The soil was watered to field capacity every second day up to 145 d in 1994 and 167 d in 1995. The plants were sprayed weekly with Vendex™ (fenbutatin-oxide) (Dupont Co., Wilmington, DE) (for mite control) and Safer's Insecticidal Soap (Safer Inc., Concord, MA) (for white fly control). The daily, average greenhouse temperature varied between 18 and 24°C in 1994 and between 18 and 30°C in 1995. Solar irradiance varied between 150 and 300 μmol m^{-2} s^{-1} over the season in 1994 and between 150 and 465 μmol m^{-2} s^{-1} in 1995. A completely randomized design was used with the four water-stress treatments and the two cultivars in a factorial arrangement. There were three replicate pots per treatment.

The water stress treatments, which were started 145 d after sowing in 1994 and 167 d in 1995, included watering to 100, 75, 50 and 25% field capacity, henceforth referred to as low, medium, high and severe water stress, respectively. Water was applied every second day at noon. The pots were watered to 4.9, 4.5, 4.1 and 3.6 kg to achieve low, medium, high and severe water stress, respectively.

Soil water tension was measured using a soil moisture tensiometer (Tensimeter, Soil Measurement Systems, Las Cruces, NM) buried to a depth of 0.1 m in each pot. Readings were taken 24 h after each watering. The soil tension values averaged over the experimental period at low, medium, high and severe water stress were 17.0 ± 4.3, 40.3 ± 4.6, 53.8 ± 4.6 and 73.9 ± 4.3 kPa, respectively. To quantify the water stress within plants, leaf water potential (ψ_L) was measured at midday 2 d prior to root harvest.

Plants were harvested 174 and 199 d after sowing in 1994 and 1995, respectively. Soil was carefully removed from the roots, which were then separated from the shoots. The carrot roots were gently cleaned with paper towels and used for various measurements as follows: three carrots from each replication (pot) were used to monitor weight loss during storage, one carrot to determine root water (ψ_R) and osmotic ($\psi_{\pi R}$) potentials, and one carrot to determine the relative solute leakage (RSL).

Carrot size and shape

The carrot root weight (W), crown diameter (D) and length (L) were measured. The C-value (which indicates carrot shape) was calculated using the formula of Bleadsdale and Thompson (1963) and surface area (A) using the formula given below (H. Baugerød, Dept of Vegetable Crops, Agric. College of Norway, Vollebekk, Norway, pers. comm.):

$$C = W/(3.142 \times R^2 \times L)$$
$$A = (4 \times C \times 3.142 \times R \times L)/(1 + C)$$

where R = D × 0.5. Since the specific gravity of carrots is approximately unity (Bleadsdale and Thompson, 1963), carrot weight in grammes (W) gives an accurate measure of root volume (V). The surface area/weight ratio [the specific surface area (SSA)] was, therefore, used to estimate the surface area/volume ratio. Transpiration coefficient (weight loss per unit surface area) was also calculated.

Moisture loss during storage

After their size and shape measurements were recorded, the carrots were placed in 0.10 m × 0.22 m plastic bags perforated with nine, 4 mm diameter holes and incubated at 13°C and 32 ± 4% r.h. (Model 52 Incubator, Sheldon Manufacturing Inc., Cornelius, OR). Carrot weight loss was monitored every second day for 20 d. Carrots with higher weight loss were considered to have a shorter shelf life. Preliminary studies showed that weight loss during storage at 13°C and 32% r.h. was mainly due to moisture loss. Respiration accounted for a negligible portion of weight loss during 21 d of storage under these conditions.

ψ_L, ψ_R and $\psi_{\pi R}$ measurements

Using a cork borer, 3 mm diameter discs were excised from the third leaf from the shoot tip. The discs were placed in the sample well of a Thermocouple Psychrometer chamber (Model C-52, Wescor Inc., Logan, UT) and connected to a Dewpoint Microvoltmeter (Model HR-33T, Wescor Inc., Logan, UT) in the psychrometer mode calibrated with NaCl standards. During ψ_L measurement, the sample well was placed in a polystyrene container to minimize thermal gradients; the temperature was maintained at 22 ± 2°C. Samples were left for 30 min, which was found in preliminary studies to be adequate to establish thermal and vapour equilibrium.

ψ_R was measured 2 h after harvesting. Cores (30 mm long) excised longitudinally from the phloem parenchyma using a cork borer were cut into 1 mm thick × 3 mm diameter discs and ψ_R was measured using the psychrometric method described above.

$\psi_{\pi R}$ measurements were made on the same carrots used for ψ_R measurements described above. Shredded phloem parenchyma tissue was stored in a freezer at −85°C for two weeks, thawed at room temperature for 10 min, crushed with a motor and pestle, and the sap expressed through a double layer of Miracloth (Calbiochem-Novabiochem Corporation, La Jolla, CA). $\psi_{\pi R}$ of the sap was measured by the depression of freezing point method using a thermocouple connected to a micrologger (21-Micrologger, Campbell Scientific Inc., Logan, UT) calibrated with NaCl standards.

Relative solute leakage measurement (RSL)

RSL from the carrot root tissues from different water-stress treatments was measured to determine cell membrane integrity. Carrot root cores (30 mm long), excised longitudinally from the phloem parenchyma using a cork borer, were cut into 1 mm thick × 4 mm diameter discs. The discs were rinsed three times and incubated in 25 ml of deionized distilled water in 50 ml glass jars (20 discs per jar) at 26 ± 2°C. After 24 h, absorbance of the incubation medium at 280 nm was measured using a spectrophotometer (Model UV 160, Shimadzu, Japan). This variable is approximately proportional to solute content (Toivonen, 1992). Following measurements, the tissue integrity was destroyed by freezing at −85°C as described above. After thawing, absorbance of the bathing medium was measured to estimate the total solute content of the tissue. RSL was expressed as the ratio of the absorbance before freezing to that after tissue disintegration by freezing.

Statistical analysis

Analysis of variance and regression analysis were carried out using the SYSTAT software (Wilkinson *et al.*, 1992) and means separated by the least significant difference (LSD) method. To determine which factors explain the variance in postharvest moisture loss most, stepwise multiple regression analysis was carried out on variables significantly affected by preharvest water stress. The water stress treatments were coded 1, 2, 3 and 4 in order of increasing percent moisture loss (W^P). Data were fitted to the model:

$$W^P = b_0 + b_1 \times WS + b_2 \times Cv + b_3 \times W + b_4 \times D + b_5 \times SSA + b_6 \times \psi_R + b_7 \times \psi_{\pi R} + b_8 \times RSL$$

where WS, the water stress treatment, D, the crown diameter, Cv, cultivar, and b_0 to b_8, the partial regression coefficients. The model with the highest R^2 (Steel and Torrie, 1981) value and the minimum Mallow's coefficient (Cp value) (Neter *et al.*, 1990) was chosen as the best one. While only experiments conducted in 1995 are described, similar results were obtained in 1994.

RESULTS

Effect of preharvest water stress on carrot size and shape

Carrot D and W decreased with increase in preharvest water stress in both cultivars (Table I). Water stress had no significant effect on carrot L and C in either cultivar. The SSA increased with increase in water stress. SSA did not differ between the two cultivars.

Effect of preharvest water stress on moisture loss of carrots

In general, both 'Eagle' and 'Paramount' carrots lost the least moisture at low preharvest water stress and the most at severe water stress (Figure 1). In 'Eagle', this trend became significant by day four; severely water stressed carrots started to lose more moisture than carrots from other treatments. There was no significant difference in moisture loss between treatments in 'Paramount' for up to 12 d, when the moisture loss of the severely stressed carrots was significantly higher than that of the three other treatments. The percent moisture losses in low and severely water stressed carrots were 14.1 and 20.5, respectively in 'Eagle' and 13.7 and 19.7, respectively in 'Paramount' on day 20 of storage.

Transpiration per unit surface area, in general, increased with increased water stress (Figure 2). The results were similar in both cultivars.

Effect of preharvest water stress on water potential and its components

ψ_L decreased with increase in preharvest water stress in both cultivars (Table II). The ψ_L of high and severely water stressed 'Eagle' carrots were significantly lower than the low and medium water stressed carrots. The low water stressed 'Paramount' carrots had the highest ψ_L and the severely stressed carrots the lowest.

ψ_R significant decreased in the high and severely, compared with low and medium, water stressed carrots in both cultivars. There was no difference in ψ_R between the low and medium water stressed carrots, and between the high and severe water stressed carrots. $\psi_{\pi R}$ decreased with increasing water stress in 'Eagle'. However, it was significantly lower only in the severely water stressed 'Paramount' carrots.

RSL

The RSL was significantly higher in the severely water stressed 'Eagle' carrots than in those of other treatments (Table II). In 'Paramount' carrots it was low in both low and medium water stressed carrots and high in high and severely water stressed carrots.

Stepwise multiple regression analysis

The best subset model obtained by backward stepping and the optimum Mallow's coefficient (Cp value) (R^2 = 0.49, $P \leq 0.05$, Cp = 0.61) showed that

TABLE I

Effect of preharvest water stress on root length (L), crown diameter (D), weight (W), C-value, and specific surface area (SSA) in carrots cvs Eagle and Paramount

	Eagle					Paramount				
Water stress	L (mm)	D (mm)	W (g)	C	SSA (cm^2 g^{-1})	L (mm)	D (mm)	W (g)	C	SSA (cm^2 g^{-1})
Low	146	33.1 a	79.2 a	0.61	1.37 b	150	36.8 a	96.6 a	0.61	1.52 c
Medium	142	30.1 ab	65.0 ab	0.61	1.57 b	160	32.9 a	78.1 ab	0.57	1.67 b
High	137	26.9 ab	48.8 bc	0.61	1.83 b	149	29.4 ab	51.9 bc	0.52	1.87 b
Severe	131	22.8 b	28.8 c	0.57	2.06 a	140	24.8 b	40.1 c	0.67	2.35 a

Means within a column followed by different letters are significantly different by LSD, $P \leq 0.05$.

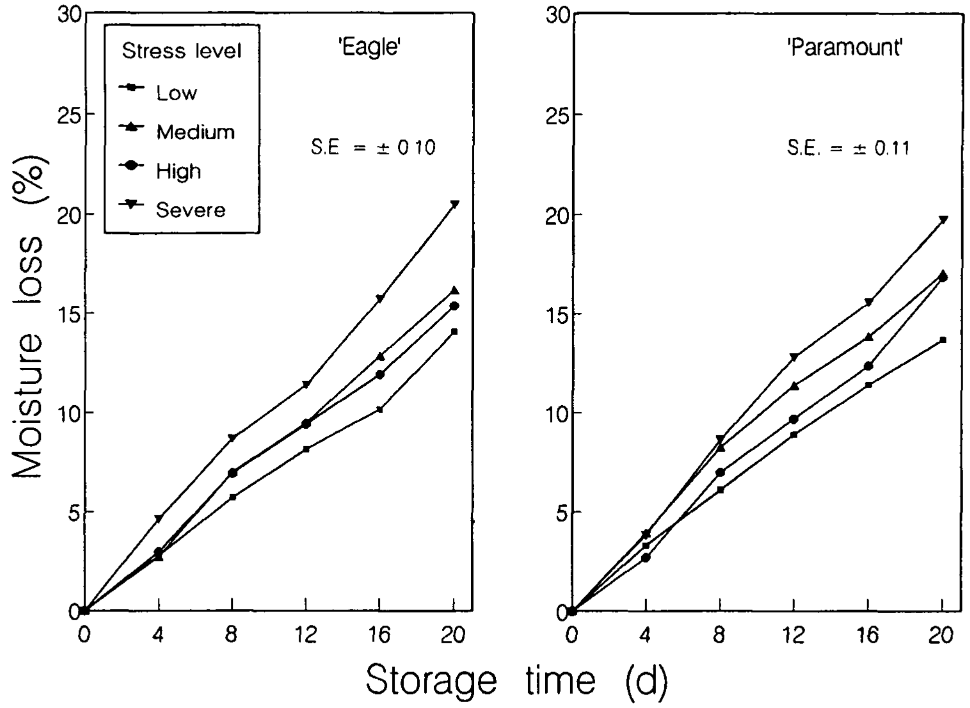

FIG. 1
Time course of percent moisture loss in cvs Eagle and Paramount stored at 13°C and 32% r.h. S.E. = overall standard error of mean

most of the variation in postharvest moisture loss could be explained by ψ_R and RSL (Table III). Thus postharvest moisture loss increased with decrease in ψ_R and increase in RSL. ψ_R, because of its high standard partial regression coefficient (b′) and high partial coefficient of determination (r^2), was more important than RSL in estimating postharvest moisture loss.

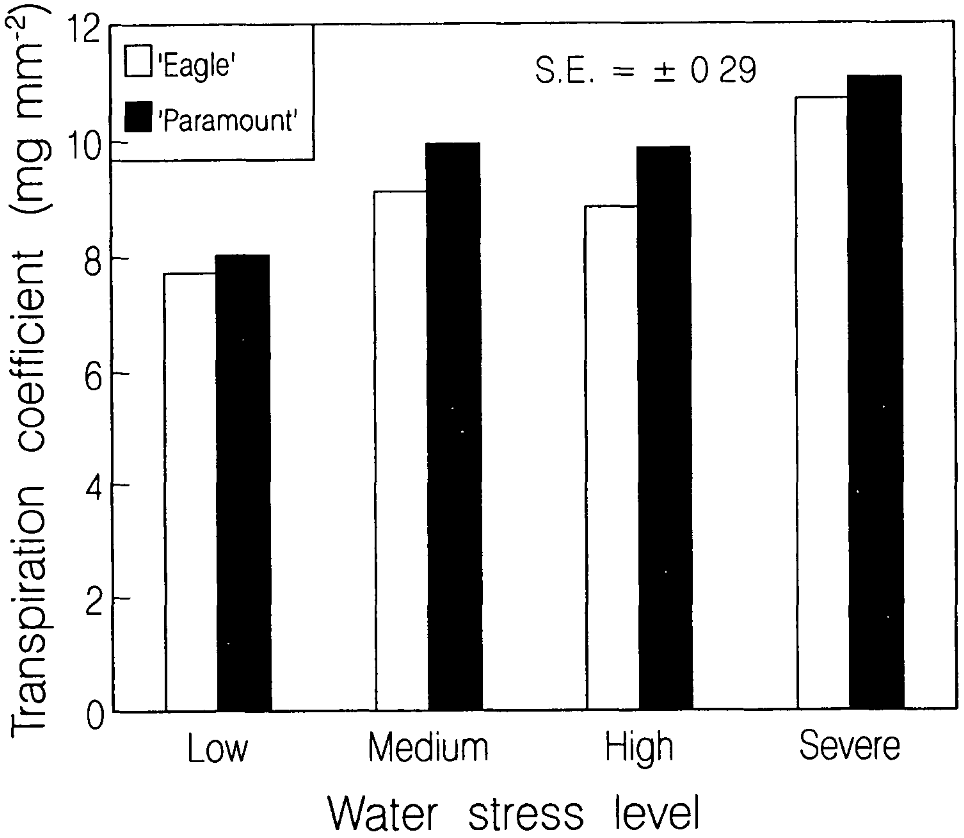

FIG. 2
Transpiration coefficient (TC) in cvs Eagle and Paramount stored at 13°C and 32% r.h. for 20 d. S.E. = overall standard error of mean.

TABLE II

Effect of preharvest water stress on leaf water potential (ψ_L), root water potential (ψ_R), root osmotic potential ($\psi_{\pi R}$), and relative solute leakage (RSL) in carrots cvs Eagle and Paramount

Water stress	Eagle				Paramount			
	ψ_L (MPa)	ψ_R (MPa)	$\psi_{\pi R}$ (MPa)	RSL (%)	ψ_L (MPa)	ψ_R (MPa)	$\psi_{\pi R}$ (MPa)	RSL (%)
Low	−1.69 a	−0.62 a	−2.00 a	5.90 b	−1.86 a	−0.91 a	−2.34 a	9.37 b
Medium	−1.89 a	−0.77 a	−2.33 ab	6.34 b	−2.07 ab	−0.91 a	−2.37 a	8.04 b
High	−2.35 b	−1.40 b	−2.77 bc	19.23 b	−2.29 b	−1.47 b	−2.87 a	39.73 a
Severe	−2.33 b	−1.66 b	−3.24 c	33.96 a	−2.94 c	−1.56 b	−3.61 b	39.98 a

Means within a column followed by different letters are significantly different by LSD, $P \leq 0.05$.

Significant ($P \leq 0.05$) positive relationships between W^P and WS and SSA, and negative relationships between W^P and D, W, and $\psi_{\pi R}$ were observed. Hence, carrots with low D, W, $\psi_{\pi R}$ and high SSA and WS tended to have higher postharvest moisture loss than those with high D, W, $\psi_{\pi R}$ and low SSA and WS. D, W, SSA, $\psi_{\pi R}$, WS and Cv were not selected in the best subset model, indicating their lesser contribution to the variation in postharvest moisture loss.

DISCUSSION

Soil fertility, temperature and water content can affect postharvest moisture loss by affecting plant growth (Stanhill, 1977), structures of evaporating surfaces, and/or plant composition (e.g. sugars, amino acids and ionic substances). In this study, preharvest water stress increased post harvest moisture loss from carrots. Stepwise multiple regression analysis showed that most of the variation in moisture loss could be explained by ψ_R and RSL.

Water movement in plants is governed largely by gradients of water potential and conductance of the flow path. Plants respond to soil moisture stress (Turner and Jones, 1980; Chapman and Augé, 1994) by lowering their cell ψ_π due to accumulation of solutes (Turner and Jones, 1980), which lowers their ψ. It is expected that carrot roots with low ψ_R would have less postharvest moisture loss. However, in this study, the roots with low ψ_R had high postharvest moisture loss. This suggests the involvement of factors other than ψ_R in regulation of postharvest moisture loss.

TABLE III

The effect of various independent variables on postharvest moisture loss of carrots stored at 13°C and 32% r h

Vaiable	Full model		Best model		
	b	*b'*	*b*	*b'*	r^2
Constant	−0.09	0.00	0.20	0.00	—
WS	−0.02	−0.57	—	—	—
Cv	0.02	0.23	—	—	—
W	0.01	0.27	—	—	—
D	0.01	0.20	—	—	—
SSA	0.09	0.88	—	—	—
ψ_R	−0.06	−0.77	−0.07	0.07	0.84
$\psi_{\pi R}$	−0.02	−0.36	—	—	—
RSL	−0.01	−0.49	−0.01	0.01	0.04
R^2	0.35		0.49		
Cp			0.61		

WS = water stress level, Cv = cultivar, ψ_R = root water potential (MPa), $\psi_{\pi R}$ = root osmotic potential (MPa), RSL = relative solute leakage, D = root crown diameter (mm), SSA = specific surface area, W = root weight (g).

— = parameter not selected in the best model, Cp = Mallow's coefficient, R^2 = model correlation coefficient, r^2 = partial coefficient of determination, *b* = partial regression coefficient, *b'* = standard partial regression coefficient.

For osmotic gradient to drive water movement into cells, proper functioning of the plasma membrane is essential. In this study, RSL, a measure of plasma membrane permeability and cellular integrity (Poovaiah and Leopold, 1976; Toivonen, 1992), increased with increase in preharvest water stress. RSL was positively correlated with moisture loss in the best subset model estimating postharvest moisture loss. An increase in plasma membrane permeability may, therefore, be a major force in determining postharvest moisture loss in carrots.

Plant structures differ in transpiration coefficient, an index of the ease with which a plant surface allows transpiration to occur (van den Berg, 1987), due to differences in interstitial, cell wall and plasma membrane resistances (Kays, 1991) as indicated by RSL. Plasma membrane deterioration, as indicated by an increase in RSL, may allow a greater flux of water through plant cells, which in turn would increase transpiration coefficient. In this study, carrots at low water stress showed low RSL and had low transpiration coefficient during storage at 13°C and 32% r.h. Conversely, the carrots at severe water stress showed high RSL and had a high transpiration coefficient.

It has been shown that larger produce which has lower SSA loses less moisture in storage compared to smaller produce with higher SSA (Wills *et al.*, 1981). This proved true in this study. The smaller carrots (with low W and D) from the severe water stress treatment had higher SSA and lost the most moisture. Conversely the moisture loss was lower in the larger carrots with lower SSA. However, while SSA, D, W and Cv influenced postharvest moisture loss, their contribution was lower compared to RSL (as they were not included in the best subset model). Since the carrots had similar L- and C-values, preharvest water stress did not influence postharvest moisture loss by changing the carrot length or shape. Cultivar differences played a minor role in determining postharvest moisture loss in carrots in this study.

CONCLUSION

The results of this study show that preharvest water stress increases postharvest moisture loss of carrots thereby reducing their shelf life. Preharvest water stress which reduced the shelf life of carrots, also reduced ψ_R and increased membrane permeability. Though a decrease in root size, which increased SSA, correlated with moisture loss, regression analysis showed that it played a relatively minor role in determining moisture loss. It is, therefore, recommended that carrots should not be harvested when soil is under water stress. Irrigation to decrease soil water stress may improve the shelf life of carrots by reducing the rate of postharvest moisture loss.

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