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Growth, Nutrient Uptake and Tipburn Severity of Hydroponic Lettuce in Response to Electrical Conductivity and K : Ca Ratio in Solution

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Abstract

A commercial hydroponic nutrient solution formulation was developed to reflect the high K:N uptake of a range of vegetable crops (Huett and Dettmann, *Aust. J. Agric. Res.* 1992, **43**, 1653–65). This standard formulation had a K:N ratio of 1·7 : 1·0 and a K:Ca ratio of 1·25 : 1·00 (equivalent weight basis). Head lettuce cv. Coolguard and cv. Fame and non-heading cv. Red Mignonette were grown in recirculating culture to maturity with the standard formulation to examine the effect of electrical conductivity (EC) (0·4–3·6 dS m^{-1}) and, for the latter two cultivars, nutrient formulation K : Ca ratio (from 1·00 : 3·50 to 3·50 : 1·00) on growth, nutrient uptake and tipburn severity. Plants grown at an EC of 0·4 dS m^{-1} were N and K deficient, while recently matured leaves and youngest leaves contained the highest Ca concentrations which decreased with increasing EC. When cv. Coolguard was grown at an EC of 1·0 dS m^{-1}, N and K deficiency was eliminated and leaves contained the highest Ca concentration. Maximum fresh weight of leaf and head was recorded at 1·6 dS m^{-1} and the decline in nutrient solution N and K concentrations over the growth period was 13 and 42% respectively.

An increase in the K : Ca ratio of the formulation increased ($P < 0·05$) leaf by 13% and leaf+head fresh weight at maturity by 10% for cv. Fame whereas, for cv. Red Mignonette, a reduction in the K : Ca ratio increased ($P < 0·05$) leaf fresh weight by 29% compared with the standard formulation.

A reduction in the K : Ca ratio increased ($P < 0·05$) the Ca concentration in the youngest leaves of cv. Fame and of cv. Red Mignonette at 1·6 and 3·6 dS m^{-1}. Leaf K concentrations were generally reduced ($P < 0·05$) by low EC and low K : Ca ratio. Hot conditions led to tipburn developing in cv. Red Mignonette at the 2 week harvest. The number of leaves $plant^{-1}$ with tipburn at maturity (week 3) was reduced ($P < 0·01$) from 23·1 to 4·4 as EC was reduced from 3·6 to 0·4 dS m^{-1} and was reduced ($P < 0·05$) from 15·2 to 12·3 as the nutrient formulation K : Ca ratio was reduced from 3·5 : 1·0 to 1·25 : 1·00. Over the last week of the growth period, the number of leaves with tipburn remained stable at an EC of 0·4 dS m^{-1} whereas, at 3·6 dS m^{-1}, the number of leaves with tipburn increased by 253%.

Tipburn developed in young leaves of cv. Red Mignonette which had a Ca concentration range from 1·7 to 3·2 g kg^{-1} and was generally absent from recently matured leaves which had a Ca concentration of 11·0 g kg^{-1}. Young leaves of the tolerant cv. Fame had a Ca concentration of 5·9 g kg^{-1}.

Keywords: calcium, electrical conductivity, hydroponic, lettuce, potassium, tipburn.

Introduction

Rapid expansion of commercial lettuce production in recirculating nutrient solution (hydroponic) culture occurred along the East Coast of Australia following

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the development of a nutrient formulation by Helyar (1980). The composition reflected general plant nutrient content where the concentrations of the dominant nutrients, K and N, were the same.

Commercial hydroponic management attempts to maintain a stable nutrient supply and a survey of commercial hydroponic lettuce growers using the Helyar formulation indicated very low K (<30 mg L^{-1}) and high N (>400 mg L^{-1}) concentrations in their nutrient solutions compared with original concentrations of around 150 mg L^{-1} (Huett unpublished data). Nutrient uptake studies demonstrated a K:N ratio of 1·90:1·00 for head lettuce (Huett and Dettmann 1992) and 1·4:1·0 for butterhead lettuce (Schippers 1980). These ratios are much higher than in the Helyar formulation and may contribute to nutrient imbalances and low growth rates in commercial hydroponic systems.

Helyar (1980) evaluated his formulation at an electrical conductivity (EC) of 1·1 dS m^{-1}, although growers subsequently increased this to 2·0–2·5 dS m^{-1} (Huett unpublished data) in line with Dutch recommendations (Sonneveld and Straver 1988) and consistent with the desirable range for butterhead lettuce (Willumsen 1984). Both heading and non-heading cultivars are grown hydroponically in Australia and sound recommendations on EC control are required.

In a commercial hydroponic system, the nutrient supply tank volume is automatically held constant and nutrient depletion and pH drift require regular adjustment. In most commercial systems, the daily adjustment is made manually and the optimum time will depend on the diurnal pattern of nutrient uptake and the effect of EC and pH on lettuce growth and quality. There are no published data on the diurnal uptake pattern for lettuce, although Creswell (unpublished data) reported a higher rate of nutrient solution EC decline during the day than the night. Tomatoes (Adams 1990; Le Bot and Kirkby 1992) and cucumbers (Schippers 1980) have a substantially higher NO_3 and K uptake during the day than the night, while daytime Ca uptake is slightly higher than at night (Ho 1989).

Tipburn can cause serious losses from mid-spring to mid-autumn. Young leaves have a lower Ca concentration than older leaves and the former are most susceptible to marginal necrosis, a characteristic symptom of tipburn (Collier and Tibbitts 1982). There are conflicting reports on the effect of nutrient solution EC and Ca supply on lettuce growth and Ca uptake (Willumsen 1984; Creswell 1991). Root pressure at night is an important Ca uptake mechanism which alleviates tipburn in strawberry (Bradfield and Guttridge 1979) and therefore diurnal nutrient uptake, nutrient solution EC and K:Ca ratio may affect growth and tipburn incidence of hydroponic lettuce.

This paper examines the diurnal pattern of nutrient uptake by lettuce, the effect of nutrient solution EC and nutrient formulation K:Ca ratio (both affect nutrient solution Ca supply) on lettuce growth, nutrient uptake, change in nutrient solution composition over time and tipburn severity.

Materials and Methods

Experimental Hydroponic Unit

The design of the unit was very similar to a commercial system and consisted of 10 tables of six 6·1 m long channels made by cutting 110 mm polyvinyl chloride stormwater pipe in half, lengthwise. The channels on each table were spaced at 310 mm centres, supported by six timber cross pieces with adjustable legs and filled with a washed 8–10 mm quartz gravel. The tables were approximately 1·5 m high with a 2° slope lengthwise. Polyethylene drums were located at the bottom of channels as nutrient supply tanks for recirculating the nutrient solution.

Each drum contained a submersible pump which irrigated through three emitters along each channel at a combined rate of 1 L min^{-1}. The flow rate of each emitter was adjusted to give a ratio of 3·5 : 2·5 : 1·0 at 2 m intervals down the channel. This achieved a constant flow rate in the channel and nutrient solution continually drained from the bottom end into the drum. The four centre channels on each table were independent experimental plots (40 total) with separate nutrient supply tanks calibrated at 180 L. Each channel held 21 lettuce plants. The outside channels were used as buffers and for each pair of tables, the four outside channels were linked to a common reservoir calibrated at 245 L.

The pumps were run on a sequence of approximately 120 s on/380 s off. This kept the gravel wet and achieved adequate drainage. Lettuce plants were spaced at 290 mm along the channels.

Leaf Sampling and Nutrient Analyses

In the nutrient solution EC experiment with head lettuce cv. Coolguard, at 9 weeks after transplanting (maturity), the head and youngest fully expanded leaves (YFEL) were analysed for total N, K, Ca, Mg, P, Fe, Cu, Zn and Mn.

In the EC×K : Ca experiment with head lettuce cv. Fame, at week 4, the three youngest and innermost head leaves (3YL) and at week 6 (maturity), the 3YL and head were analysed for K, Ca and Mg. At week 6, the YFEL were analysed for total N, P, K, Ca, Mg, Fe, Cu and Zn.

In the EC×K : Ca experiment with cv. Red Mignonette lettuce, at week 2 and week 3 (maturity), the 3YL were analysed for K, Ca and Mg. At week 3, YFEL were analysed for total N, P, K, Ca, Mg, Fe, Cu and Zn.

Water-soaked and marginally necrotic leaves were observed on 2 week old plants of cv. Red Mignonette on 11 December 1990, after 2 days with maximum temperatures of 29·3 and 30·6°C relative humidities (9·00 a.m.) of 68% and 64%, and wind runs of 390 and 433 km day^{-1} respectively compared with December means (1966–91) of 26·8°C, 75% and 244 km day^{-1} respectively. At each harvest, tipburn severity was recorded as the number of leaves with marginal water soaking and necrosis, and included young, immature leaves.

Standard Nutrient Solution Formulation

The formulation developed by Helyar (1980) was modified by increasing the K : N ratio from 1·0 : 1·0 to 1·7 : 1·0 to reflect the high K uptake in lettuce (Huett and Dettmann 1992), trebling the iron (Fe), doubling the molybdenum (Mo) and halving the boron (B) concentration to reflect trace-element concentrations in experimentally evaluated formulations (Smith *et al.* 1983) (Table 1). The K : Ca ratio (equivalent weight basis) was 1·25 : 1·00.

Separate stock solutions were prepared from calcium nitrate and iron chelate (solution A) and the remaining nutrients (solution B). Nutrient solution in the drums was prepared by diluting equal volumes of A and B to a predetermined EC with water which contained a negligible concentration of nutrients. The pH of the nutrient solution was maintained at 6·0–7·0 and, with only 1% of the total N as ammonium, no pH adjustment was required during the initial growth stages of lettuce. During the middle growth stages, the pH became slightly acid and calcium and potassium hydroxides were used alternately to adjust the pH without changing the nutrition solution K : Ca ratio. During the latter growth stages, the pH became slightly alkaline and phosphoric and sulfuric acids were used to adjust the pH.

Diurnal Nutrient Uptake

In each experiment, seedlings were raised in a peat and vermiculite mixture containing commercial rates of fertilizer. Cell size in the seedling trays was 30×30×50 mm. Ten days after emergence, plants were irrigated with the standard nutrient solution at an EC of 1·2 dS m^{-1}. The seedlings were moved outdoors from the glasshouse several days prior to transplanting at the 2–3 true leaf growth stage.

Diurnal nutrient uptake was measured on one reservoir draining four channels. The volume of the reservoir was maintained at 245 L by adjusting and recording the volume each hour. Ten minutes before the hour, the nutrient pump cycle was disabled to allow most of the volume of nutrient solution to drain from the channels into the reservoir. The nutrient solution was thoroughly stirred and a sample of nutrient solution was taken for chemical analyses.

An experiment was conducted with 6 week old head lettuce plants of cv. Coolguard from 28–29 September 1989. The maximum and minimum temperatures were 22° and 14° respectively. The initial conductivity was 2·0 dS m^{-1} and represented the common commercial EC. The experiment was conducted on near cloudless days and the maximum photosynthetic photon flux density of 2066 μE s^{-1} m^{-2} was recorded at 1200 h on 28 September 1989. Bright sunshine, recorded on a Stokes sunshine recorder located near the experimental site, extended from 0900 to 1700 h and then from 600 to 1100 h. Linear regressions were used to fit the decline in EC and nutrient concentration over the full experimental period. Separate linear regression analyses were also used for the initial period of bright sunshine, the dark period and the final period of bright sunshine. A t test was used to compare regression coefficients.

EC Experiment

The experiment consisted of the head lettuce cv. Coolguard grown with the standard nutrient formulation (Table 1) at EC values of 0·4, 1·0, 1·6, 2·4 and 3·6 dS m^{-1}. Each treatment was replicated eight times (21 plants $plot^{-1}$) and the 40 plots were arranged in 10 balanced incomplete blocks. Electrical conductivity, pH and nutrient solution volume (180 L) were adjusted three times each week.

Table 1. Composition of standard nutrient solution

Solution	Compound	g L^{-1}	Solution	Compound	g L^{-1}
A	$Ca(NO_3)_2.4H_2O$	142·6	B	H_3BO_3	0·35
	Fe EDTA	5·6		$ZnSO_4.7H_2O$	0·20
B	$NH_4H_2PO_4$	1·7		$MnSO_4.H_2O$	0·20
	KH_2PO_4	26·4		$CuSO_4.5H_2O$	0·035
	KNO_3	136·7		$Na_2MoO_4.2H_2O$	0·01
	$MgSO_4.7H_2O$	58·1			

Lettuce seedlings were transplanted on 10 August 1989 and plants were harvested for fresh weight determination 2, 5 and 9 weeks later. The latter harvest represented crop maturity based on head size and firmness. At each harvest, three plants were removed from each plot at random although, at maturity, plants which previously had a neighbouring plant removed were avoided.

Nutrient solution was sampled from the drum supplying each plot at transplanting and at final harvest for chemical determinations.

EC×K : Ca Experiments

Treatments were 3 ECs (0·4, 1·6 and 3·6 dS m^{-1})×3 formulations with K : Ca ratios (equivalent weight basis of 3·5 : 1·0, 1·25 : 1·00 and 1·0 : 3·5). Each treatment was replicated four times in a completely random design.

The formulation with a K : Ca ratio of 1·25 : 1·00 was the standard formulation. The two other K : Ca ratios were achieved by altering the concentrations of calcium nitrate and potassium nitrate. The respective concentrations were K : Ca of 3·5 : 1·0, 71·3 and 199·4 g L^{-1}; K : Ca of 1·0 : 3·5, 249·5 and 42·7 g L^{-1}. In the three formulations, K+Ca concentrations (equivalent weight) were constant and the N concentration varied by 10%. The K : N ratio was 0·68 : 1·00 for the low K formulation and 2·15 : 1·00 for the high K formulation.

An experiment was conducted with head lettuce cv. Fame transplanted on 26 February 1990 and harvested for fresh weight determination 4 and 6 weeks later. The latter harvest represented crop maturity based on head size and firmness. At each harvest, three plants were removed from each plot at random.

A similar experiment was conducted with Henderson's cv. Red Mignonette, a non-heading fancy lettuce and highly susceptible to tipburn. Seedlings were transplanted on 27 November 1990 and harvested for fresh weight determination 2 and 3 weeks later. The latter harvest represented maturity based on plant size. At each harvest, five plants were removed from each plot at random. Nutrient solution was sampled from the tank supplying each plot at transplanting and at final harvest for chemical determinations.

In each experiment, fresh plant parts were dried at 70° for 24 h for chemical determinations.

Chemical Determinations

Dried plant material was ground to pass a 1 mm sieve. Total N was determined on a semi-micro Kjeldahl digest, P by the 'molybdenum blue' method and, K, Ca, Mg, Fe, Cu, Zn and Mn in perchloric acid digestions were determined by atomic absorption spectrophotometry (AAS) (Huett and Rose 1988).

Nutrient solutions were analysed for nitrate-N (Mullen and Ridley 1955), P by the 'molybdenum blue' method and K, Ca, Mg, Fe, Zn, Mn and Cu were read by atomic absorption spectrophotometry (Huett and Rose 1988).

Results

Diurnal Nutrient Uptake

The decline in Ca+Mg+K nutrient concentration (y) over the 27 h sampling period (hours after 0900 h (x)) was described by the regression equation

$$y = 401\cdot31 - 3\cdot41(\pm 0\cdot37)x \qquad (R^2 = 0\cdot78,\ P < 0\cdot001).$$

No relationship could be detected ($P > 0\cdot05$) when separate regression equations were fitted to the initial period of bright sunshine (1000–1700 h), the dark period (1800–500 h) and the final period of bright sunshine (600–1100 h).

The EC, which gives an accurate indication of total nutrient concentration, declined linearly over the 27 h sampling period (Fig. 1).

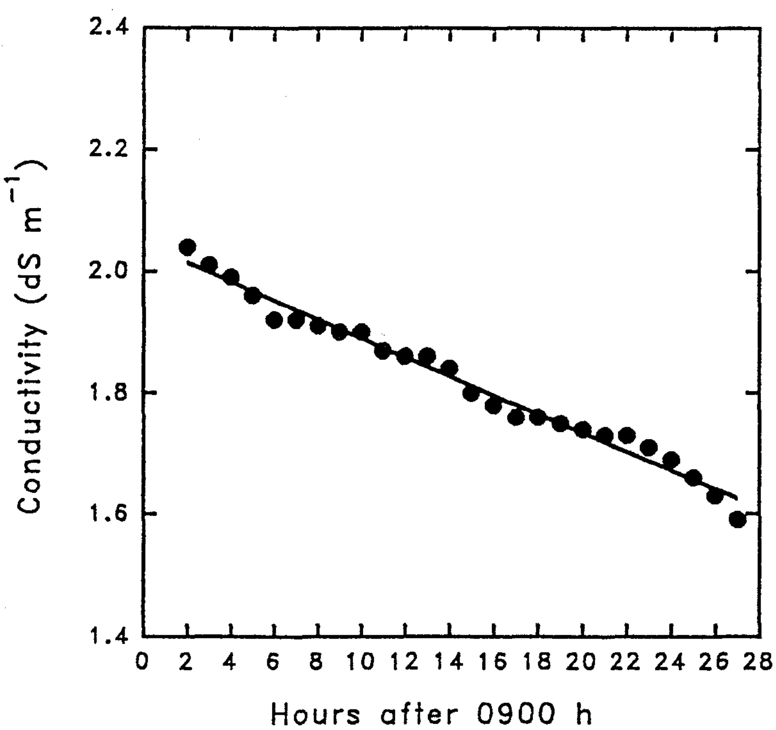

Fig. 1. Diurnal change in EC, 28–29 September 1989. Regression for EC (y) and hours after 900 h (x) is: $y = 2\cdot045 – 0\cdot016\ (\pm 0\cdot0004)\ x$ ($R^2 = 0\cdot98$, $P < 0\cdot001$)

Linear regressions also fitted the initial period of bright sunshine ($b = -0\cdot021\pm0\cdot014$, $R^2 = 0\cdot94$, $P < 0\cdot001$), the dark period ($b = -0\cdot015\pm0\cdot014$, $R^2 = 0\cdot95$, $P < 0\cdot001$) and the final period of bright sunshine ($b = -0\cdot028\pm0\cdot008$, $R^2 = 0\cdot98$, $P < 0\cdot001$). While the rate of nutrient uptake, estimated by the correlation coefficient b, was higher during the bright sunshine periods than at night, t-tests indicated no difference ($P \geq 0\cdot05$).

Plant water use was 730 mL plant^{-1} day^{-1} and it followed a diurnal pattern with maximum water use at 1400 h and minimum water use at 2400 h.

Fresh Weight of Plant

EC experiment cv. Coolguard

Lettuce growth responded ($P < 0\cdot05$) to EC, with maximum growth being recorded over the 1·0–1·6 dS m^{-1} range (Fig. 2). At the 2 (Fig. 2*a*) and 5 week harvests (Fig. 2*b*), maximum fresh leaf weight was recorded at 1·0 dS m^{-1}. At the 9 week harvest (Fig. 2*c*), head growth in particular was very responsive to EC and was reduced ($P < 0\cdot05$) at 0·4 and 2·4 dS m^{-1} and further reduced ($P < 0\cdot05$) at 3·6 dS m^{-1}.

Visually, plant growth at all ECs appeared satisfactory, nutrient deficiency and toxicity symptoms were absent, and they all produced heads of an acceptable commercial size.

EC×K:Ca experiments cvv. Fame and Red Mignonette

Conductivity affected ($P < 0\cdot05$) the fresh weight of leaf at the 4 and 6 week harvests and fresh weight of leaf and of head at week 6 of cv. Fame (Fig. 3). The highest weights were recorded at an EC of 1·6 dS m^{-1}.

The K:Ca ratio of the nutrient formulation had no effect ($P \geq 0\cdot05$) on plant weight at week 4 whereas, at week 6, increasing the ratio from 1·00:3·50 to 3·50:1·00 increased ($P < 0\cdot05$) the fresh weight of leaf and leaf+head from 433 and 801 g to 540 and 982 g respectively.

Treatments had no effect ($P \geq 0\cdot05$) on the fresh weight of leaf of cv. Red Mignonette lettuce at the 2 week harvest. At the 3 week harvest, there was an interaction ($P < 0\cdot01$) between EC and K:Ca ratio (Fig. 4).

Leaf growth was similar ($P \geq 0\cdot05$) at 0·4 and 1·6 dS m^{-1} and declined ($P < 0\cdot05$) at 3·6 dS m^{-1} with the standard nutrient formulation. An EC of 1·6 dS m^{-1} was optimum for growth with the high and low K:Ca formulations. At 1·6 and 3·6 dS m^{-1}, the largest Red Mignonette plants were produced with the 1·0:3·5 K:Ca formulation.

Change in Nutrient Solution Composition

EC experiment cv. Coolguard

The concentration of nutrients in the solution changed over the crop growth period and was affected ($P < 0\cdot01$) by EC (Fig. 5).

The % change in concentration increased with decreasing conductivity and was in the order Mg > Ca (positive) > K > N (negative). The % increase in P concentration exceeded that for Mg over the 1·6–3·6 dS m^{-1} EC range. Trace element concentrations were affected ($P < 0 \cdot 01$) by EC and either consistently increased or decreased over the EC range. The maximum % change in concentration over the growth period at ECs of $1 \cdot 0$–$1 \cdot 6$ dS m^{-1} were Fe, −94±2; Cu, −92±8; and Zn,+138±29.

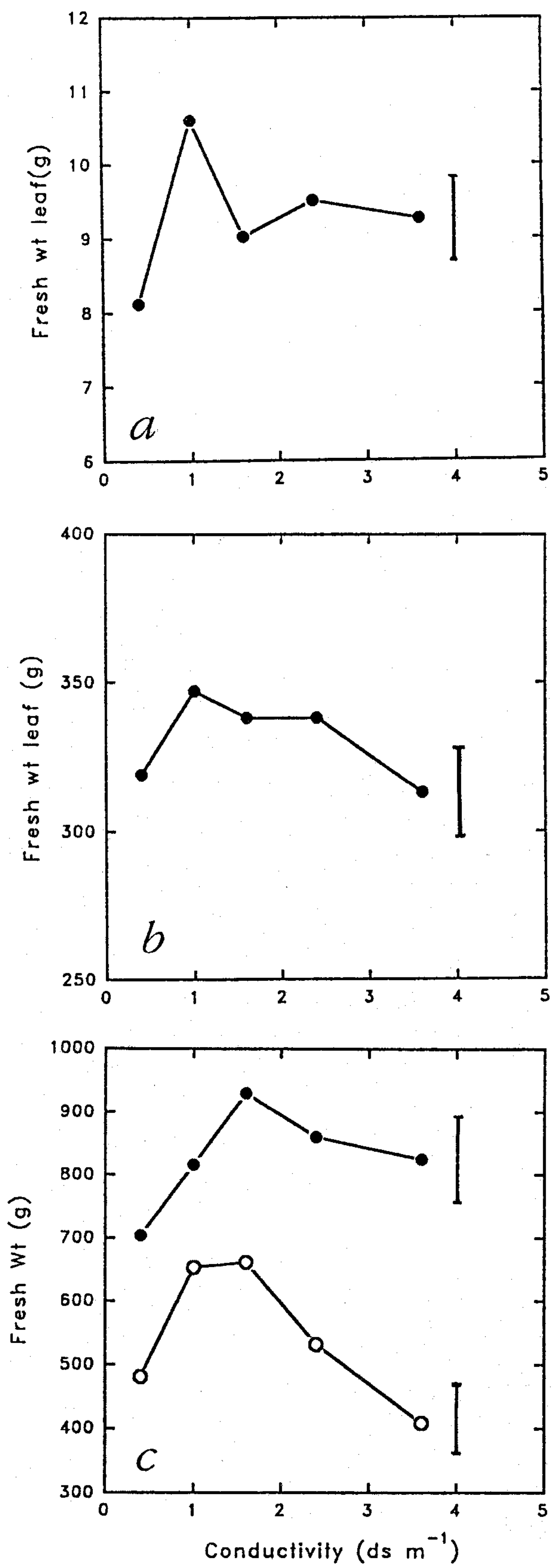

Fig. 2. Effect of nutrient solution EC on fresh weight of (*a*) leaf at week 2 (●); (*b*) leaf at week 5 (●); and (*c*) leaf (●) and head (○) at week 9 of head lettuce cv. Coolguard. Vertical bars indicate l.s.d. (P=$0 \cdot 05$).

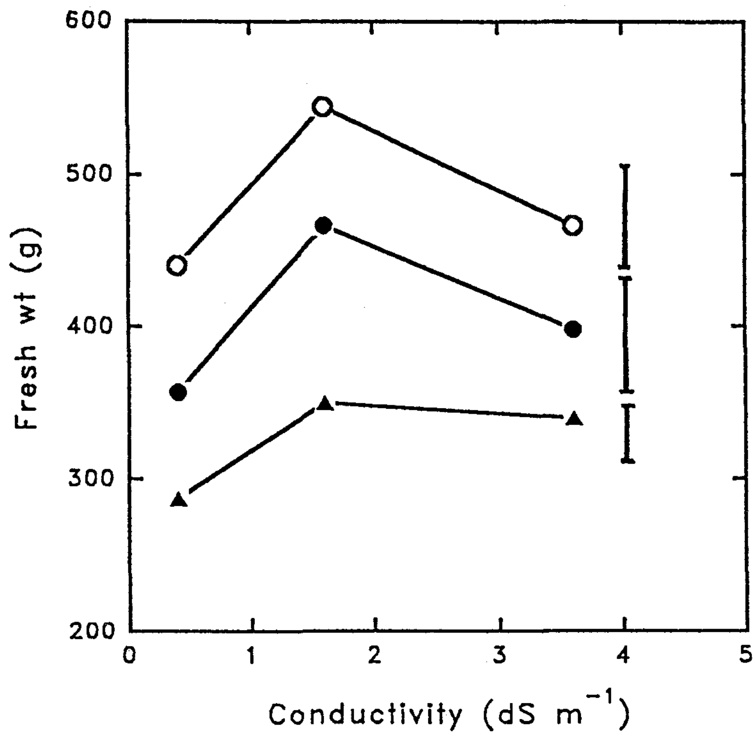

Fig. 3. Effect of nutrient solution EC on fresh weight of leaf at week 4 (▲), leaf (○) and head (●) at week 6 of head lettuce cv. Fame. Vertical bars indicate l.s.d. (P=0·05)

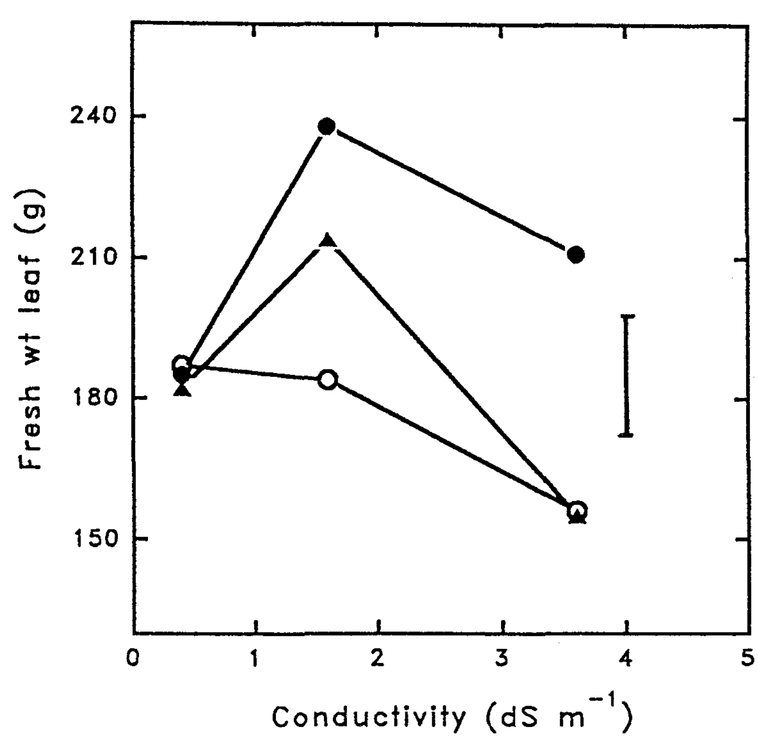

Fig. 4. Effect of nutrient solution EC on fresh weight of leaf of cv. Red Mignonette lettuce at week 3 with formulations having K:Ca ratios of 1·00 : 3·50 (●), 1·25 : 1·00 (○) and 3·50 : 1·00 (▲). Vertical bar indicates l.s.d. (P=0·05).

EC×K:Ca experiments cvv. Fame and Red Mignonette

The Ca and Mg concentrations in the nutrient solution increased by 19±7% and 8±4% respectively over the crop growth period at an EC of 1·6 dS m^{-1} and were not affected ($P \geq 0{\cdot}05$) by treatment. The N and K concentrations decreased ($P < 0{\cdot}01$) by 69% and 66% respectively over the growth period at an EC of 0·4 dS m^{-1}. At higher EC's, N concentration was stable ($P \geq 0{\cdot}05$)

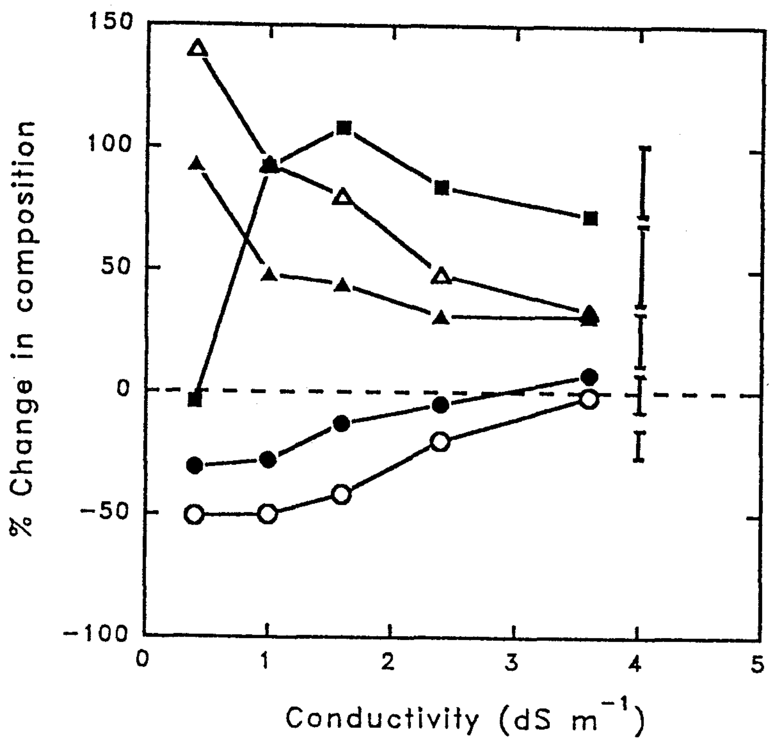

Fig. 5. Effect of nutrient solution EC on change (%) in concentration of N (●), K (○), Ca (▲), Mg (△) and P (■) over the crop growth period with head lettuce cv. Coolguard. Vertical bars indicate l.s.d. (P=0·05).

while K concentration decreased ($P < 0 \cdot 01$) by 23% at an EC of 1·6 dS m^{-1} and was stable at an EC of 3·6 dS m^{-1}.

The decrease ($P < 0 \cdot 01$) in nutrient solution K concentration was reduced from 47 to 8±2% as the K:Ca ratio in the solution was increased from 1·0:3·5 to 3·5:1·0.

Plant Nutrient Composition

EC experiment cv. Coolguard

The concentrations of N, K and Mn in YFEL and head decreased ($P < 0 \cdot 05$) with decreasing EC at the week 9 harvest. The highest Ca concentrations were recorded at an EC of 1·0 dS m^{-1} in both YFEL and head and were reduced ($P < 0 \cdot 05$) at 0·4 dS m^{-1} and as EC increased to 3·6 dS m^{-1}. The Mg concentrations in YFEL and head decreased ($P < 0 \cdot 05$) with increasing EC. The results for N, K, Ca, Mg and Mn are presented in Table 2.

The YFEL Fe concentration increased ($P < 0 \cdot 05$) from 135 to 172 mg kg^{-1} as EC decreased from 3·6 to 1·0 dS m^{-1} and the head P concentration decreased ($P < 0 \cdot 05$) from 7·9 to 7·0 g kg^{-1} as EC decreased from 3·6 to 0·4 dS m^{-1}.

EC×K:Ca Ratio experiment cv. Fame

There was a significant ($P < 0 \cdot 01$) interaction between EC and K:Ca ratio for YFEL K and Ca and 3YL K concentrations at the week 6 harvest (Table 3).

The K concentration in 3YL and YFEL was reduced by low EC and low K:Ca ratio, whereas this combination increased YFEL Ca concentration. At medium and high ECs, 3YL and YFEL K concentration generally increased at the high K:Ca ratio, whereas YFEL Ca concentration was not affected by the K:Ca ratio at high EC.

Table 2. Effect of EC on nutrient concentration in YFEL and head of cv. Coolguard 9 weeks after transplanting (maturity)

EC ($dS\ m^{-1}$)	N	K ($g\ kg^{-1}$)	Ca	Mg	Mn ($mg\ kg^{-1}$)
		YFEL			
0·4	25·7	54·7	15·7	4·3	42
1·0	34·4	100·0	17·8	4·0	46
1·6	35·7	103·2	14·9	3·5	57
2·4	37·2	103·1	12·5	3·0	60
3·6	37·8	109·6	11·8	2·9	100
l.s.d.[A]	2·0	12·8	2·6	0·3	17
		Head			
0·4	26·8	39·3	4·3	1·9	11
1·0	32·6	56·3	5·0	1·9	15
1·6	32·6	56·6	4·4	1·8	19
2·4	33·2	58·7	3·9	1·8	22
3·6	35·1	64·0	3·6	1·7	35
l.s.d.[A]	2·6	7·0	0·6	0·1	3

[A] $P = 0{\cdot}05$.

Table 3. Interactions between EC and K:Ca ratio on K and Ca concentration ($g\ kg^{-1}$) in YFEL of cv. Fame 6 weeks (maturity) and 3YL 4 and 6 weeks after transplanting

EC ($dS\ m^{-1}$)	K:Ca	K 3YL-wk 4	K 3YL-wk 6	K YFEL-wk 6	Ca YFEL-wk 8
0·4	1·00:3·50	29·1	32·2	38·5	32·1
0·4	1·25:1·00	49·5	48·0	84·3	21·3
0·4	3·50:1·00	53·1	45·4	98·4	17·1
1·6	1·00:3·50	52·2	41·3	81·8	19·4
1·6	1·25:1·00	53·3	50·6	103·6	13·9
1·6	3·50:1·00	55·2	51·3	101·0	10·8
3·6	1·00:3·50	54·7	42·7	68·0	12·3
3·6	1·25:1·00	60·5	39·2	89·8	12·2
3·6	3·50:1·00	63·1	54·6	108·4	11·3
	l.s.d.[A]	5·8	8·2	8·6	1·7

[A] ($P = 0{\cdot}05$).

The Mg and Zn concentrations in YFEL at week 6 decreased ($P < 0{\cdot}01$) from 4·8 to 2·8 g kg^{-1} and from 197 to 108 mg kg^{-1} respectively as EC increased from 0·4 to 3·6 dS m^{-1}.

The N, P, Fe and Cu concentrations in YFEL at week 6 were not affected ($P \geq 0{\cdot}05$) by treatment and the mean concentrations were (g kg^{-1}) 40·1±2·6, 4·3±0·2 and (mg kg^{-1}) 189±33 and 13±5 respectively.

The Ca, Mg and K concentrations in 3YL were much lower than in YFEL and were affected by the EC and K:Ca ratio in solution. At week 4, the Ca concentration (g kg^{-1}) decreased ($P < 0{\cdot}01$) from 4·0 to 3·3 as EC increased from 0·4 to 3·6 dS m^{-1} and from 4·6 to 2·9 as the K:Ca ratio increased from 1·00:3·50 to 3·50:1·00.

At week 6, the Ca concentration in 3YL decreased ($P < 0{\cdot}01$) as EC increased from 0·4 to 3·6 dS m^{-1} and Mg concentration decreased ($P < 0{\cdot}05$) as EC

Table 4. Effect of EC and K : Ca ratio on Ca and Mg concentration (g kg^{-1}) in the three youngest leaves of cv. Fame at maturity

Nutrient solution	Ca	Mg	Nutrient solution	Ca	Mg
EC (dS m^{-1})			K : Ca ratio		
0·4	0·69	0·24	1·00 : 3·50	0·66	0·19
1·6	0·58	0·20	1·25 : 1·00	0·60	0·23
3·6	0·51	0·22	3·50 : 1·00	0·52	0·25
l.s.d[A]	0·09	0·03	l.s.d[A]	0·12	0·03

[A] $P = 0{\cdot}05$.

Table 5. Interaction between EC and K : Ca ratio on nutrient concentration (g kg^{-1}) YFEL of cv. Red Mignonette 3 weeks (maturity) and 3YL 2 and 3 weeks after transplanting

EC (dS m^{-1})	K : Ca	YFEL-wk 3 K	YFEL-wk 3 Ca	YFEL-wk 3 Mg	YFEL-wk 3 P	3YL wk 2 K	3YL wk 3 K
0·4	1·00 : 3·50	31·4	11·1	6·1	7·2	46·5	33·6
0·4	1·25 : 1·00	81·2	10·8	3·4	8·5	64·5	59·9
0·4	3·50 : 1·00	84·5	10·2	3·7	8·4	66·9	63·6
1·6	1·00 : 3·50	89·9	13·2	3·6	8·7	65·2	61·6
1·6	1·25 : 1·00	90·5	10·8	3·5	8·7	64·5	65·2
1·6	3·50 : 1·00	97·8	9·8	4·0	8·6	65·7	65·1
3·6	1·00 : 3·50	86·1	7·3	3·9	9·6	59·7	59·2
3·6	1·25 : 1·00	94·4	10·1	3·0	8·5	60·8	62·6
3·6	3·50 : 1·00	96·6	4·1	3·3	8·7	67·4	64·4
	l.s.d.[A]	9·9	2·3	0·8	0·9	5·2	4·1

[A] $P = 0{\cdot}05$.

increased from 0·4 to 1·6 dS m^{-1} (Table 4). The Ca concentration decreased ($P < 0{\cdot}01$) and the Mg concentration increased ($P < 0{\cdot}05$) in 3YL with increasing nutrient formulation K : Ca ratio.

EC×K : Ca ratio, cv. Red Mignonette

There was a significant ($P < 0{\cdot}01$) interaction between EC and K : Ca ratio for YFEL K, Ca and Mg concentrations at week 3 and for 3YL K concentrations at the week 2 and 3 harvests (Table 5).

The K concentration in 3YL and YFEL was reduced by low EC and low K : Ca ratio, whereas this combination increased YFEL Mg concentration. At medium and high ECs, the highest K concentrations were generally recorded with the high K : Ca ratio, whereas the Mg responses were inconsistent. The Ca concentration in YFEL increased with decreasing EC with the high K : Ca formulation and increased with the low K : Ca formulation as EC was reduced from 3·6 to 1·6 dS m^{-1}. At the low EC, the lowest P concentration was recorded with the lowest K : Ca formulation, whereas the opposite result was recorded at the high EC.

The mean N, P and Zn concentrations in YFEL were reduced ($P < 0{\cdot}01$) at an EC of 0·4 dS m^{-1} to 40·2, 8·0 (g kg^{-1}) and 53 mg kg^{-1} respectively. The Fe and Cu concentrations in YFEL were unaffected by EC and the mean values were 147±7 and 8·8±0·3 mg kg^{-1} respectively.

There was a significant ($P < 0{\cdot}01$) interaction between the EC and K : Ca ratio for 3YL Ca (Fig. 6) and Mg (Fig. 7) concentration at the week 3 harvest.

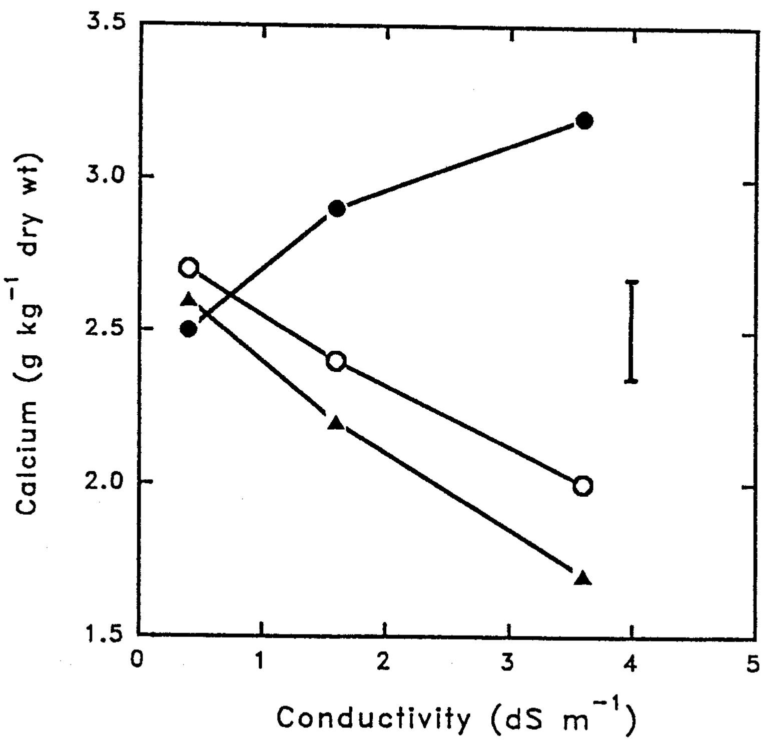

Fig. 6. Effect of nutrient solution EC on Ca concentration in the three youngest leaves of cv. Red Mignonette at K : Ca ratios of 1·00 : 3·50 (●), 1·25 : 1·00 (○) and 3·50 : 1·00 (▲) at the week 3 harvest. Vertical bars indicate l.s.d. (P=0·05).

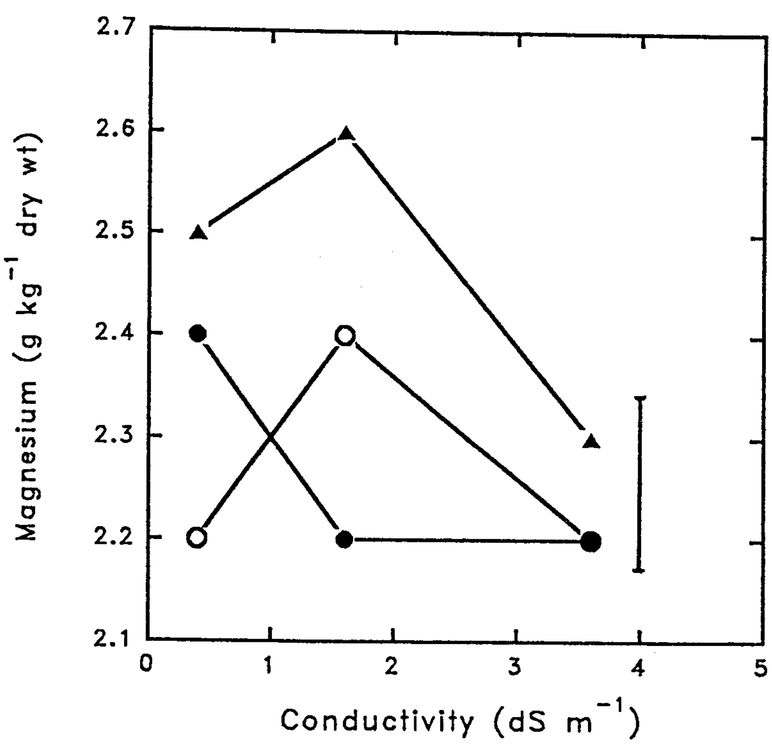

Fig. 7. Effect of nutrient solution EC on Mg concentration in the three youngest leaves of cv. Red Mignonette at K : Ca ratios of 1·00 : 3·50 (●), 1·25 : 1·00 (○) and 3·50 : 1·00 (▲) at the week 3 harvest. Vertical bars indicate l.s.d. (P=0·05).

At the lowest K:Ca ratio, 3YL Ca concentration increased with increasing EC, whereas the opposite response was recorded at the two higher K:Ca ratios. The highest Mg concentrations were recorded at an EC of 0·4 and 1·6 dS m^{-1} at the highest K:Ca ratio and they decreased at an EC of 3·6 dS m^{-1}.

Tipburn Severity

Tipburn was observed in leaves after hot, dry, windy conditions which occurred 2 days prior to the week 2 harvest. Symptoms continued to develop over the next week and at the 3 week harvest most of the leaves in the high EC treatment were affected. The number of leaves with tipburn at both harvests decreased ($P < 0 \cdot 01$) as EC decreased from 3·6 to 0·4 dS m^{--1} and the effect was most pronounced at the week 3 harvest (Fig. 8).

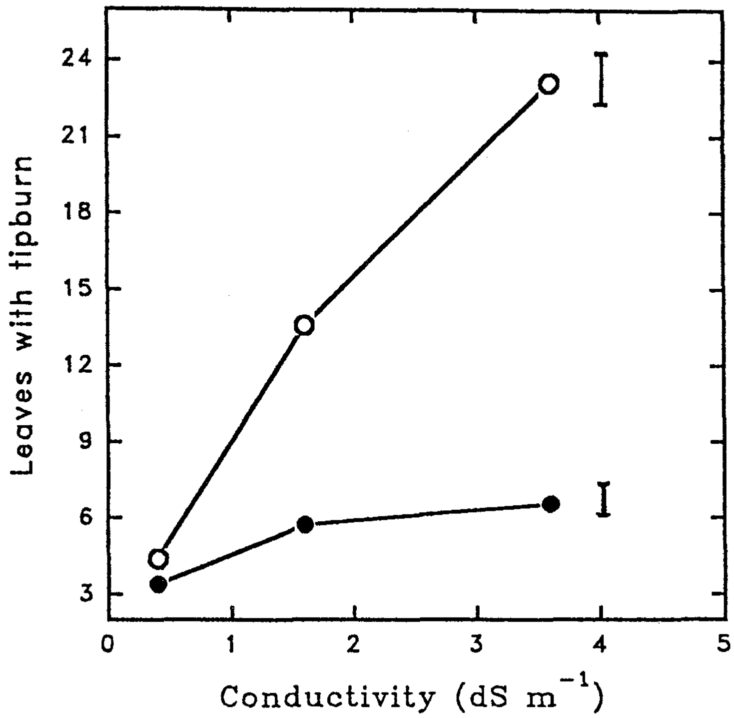

Fig. 8. Effect of nutrient solution EC on the number of leaves with tipburn of cv. Red Mignonette at the week 2 (●) and 3 (○) harvest. Vertical bars indicate l.s.d. (P=0·05).

The severity of tipburn did not increase from week 2 to 3 at an EC of 0·4 dS m^{-1}; whereas at 1·6 and 3·6 dS m^{-1}, the number of leaves with tipburn increased by 137% and 253% respectively.

At week 3, a reduction in the K : Ca ratio from 3·5 : 1·0 to 1·25 : 1·00 reduced ($P < 0 \cdot 05$) the number of leaves with tipburn from 15·2 to 12·3.

Discussion

The composition of the standard nutrient formulation developed for lettuce in the current experiments was, coincidentally, very similar to that used for commercial lettuce grown in recirculating nutrient solution culture in the Netherlands (Sonneveld and Straver 1988). The latter formulation contained half the Mg and Fe concentration of the formulations used in the current experiments while the K : N and K : Ca ratios were almost identical. The Ca : Mg ratio in mature head lettuce is 2·3 : 1·0 (Huett and Dettmann 1992) which suggests that the ratio of 7·5 : 1·0 in the Dutch formulation may lead to Mg deficiency, even though high Ca concentrations are a feature of hydroponic nutrient solutions.

A comparison of eight different nutrient formulations, including Hoagland's No. 1, No. 2 and the Long Ashton solution, showed that Fe concentration accounted for most of the differences in the growth of maize, ryegrass and white clover in sand culture (Smith *et al.* 1983). Plants grown with the Ruakura formulation consistently outyielded the other formulations and the former Fe concentration is very similar to that in the current standard formulation.

The highest fresh weight of head and/or leaf of mature heading and non-heading lettuce was consistently produced at an EC of 1·6 dS m^{-1} in the current experiments. In Dutch glasshouse experiments, butterhead lettuce was unresponsive to EC and K:Ca ratio in solution (Willumsen 1984). At an EC of 1·6 dS m^{-1}, mature head lettuce produced the highest fresh weight of leaf and leaf+head with a high K:Ca ratio formulation, whereas the opposite response was recorded for leaf fresh weight of non-heading lettuce. Maintenance of the standard nutrient solution EC at about 1·6 dS m^{-1} will minimize changes in nutrient solution composition over time, and the timing of daily adjustments to EC is not critical because nutrient concentrations are high, nutrient uptake during the day and night is similar and the small change over a few hours will not affect lettuce growth.

The low K formulation used in the current study had a similar macroelement composition to the Helyar formulation (Helyar 1980). Rapid depletion of solution K occurred for both formulations and was overcome by increasing the K concentration, the strategy adopted in developing the standard nutrient formulation. At the optimum conductivity of 1·6 dS m^{-1} for lettuce growth, the increase in growth of cv. Fame and the reduction in growth of cv. Red Mignonette, as solution K concentration increased, suggest that heading and non-heading lettuce may require different formulations.

The highest leaf tissue Ca concentrations for both head and non-heading lettuce were recorded over an EC range of 0·4–1·0 dS m^{-1}. Rapidly transpiring leaves were more responsive to EC than non-transpiring leaves. Root pressure at night has been proposed as the main Ca uptake mechanism for non-transpiring leaves of lettuce (Thibodeau and Minotti 1969; Collier and Wurr 1981; Barta and Tibbitts 1986; Creswell 1991) and strawberry (Guttridge *et al.* 1981) and is enhanced by low salinity and high humidity.

The larger and more consistent increases in Ca concentration in both young and recently matured leaves in the present study compared with those recorded by Creswell (1991) demonstrate that a constantly low salinity enhances Ca uptake more than a reduction at night only. Low salinity at night was applied because night-time root pressure, which is enhanced by low salinity, was considered to be the main Ca uptake mechanism (Creswell 1991). However, low salinity during both the day and night were effective in increasing tomato Ca uptake (Ho and Adams 1989), even though fruit accumulate more Ca at night (Ho 1989). The response to low salinity in the present study, the relatively constant diurnal rate of nutrient uptake and the significance of daytime Ca uptake by tomato (Ho 1989; Ho and Adams 1989) indicate that Ca uptake and movement within leaves is equally affected by transpiration during the day and root pressure at night.

There were differences in the Ca uptake and growth response by cultivars at constant EC to an increase in Ca supply by reducing the nutrient formulation K:Ca ratio. This resulted in an increase in Ca concentration in the youngest leaves of cv. Fame whereas, for cv. Red Mignonette, the increase, which was much greater than that for cv. Fame, was recorded at medium and high ECs only. The Ca concentration in young mature leaves of cv. Fame almost doubled when the K:Ca ratio was reduced from 3·5:1·0 to 1·0:3·5 at low EC only, whereas an inconsistent response was recorded by cv. Red Mignonette. A substantial growth response was also recorded by cv. Red Mignonette to a decrease in the

K : Ca ratio at medium and high ECs, whereas the growth of cv. Fame increased as the K : Ca ratio was increased.

The hot, dry, windy weather which preceded the rapid development of tipburn symptoms in cv. Red Mignonette lettuce was consistent with conducive conditions described by Cox *et al.* (1976), Misaghi and Grogan (1978) and Collier and Wurr (1981). The present study confirmed the work of Creswell (1991) that treatments which increase Ca accumulation in leaves reduce tipburn severity. It also confirmed the results of Willumsen (1984) that a constant reduction in salinity reduces tipburn severity and substantially exceeded the reduction in tipburn achieved by low salinity at night only (Creswell 1991). The present study, unlike Willumsen's, demonstrated that a decrease in nutrient solution K : Ca ratio reduces tipburn severity while it is less effective than a reduction in salinity. Both treatments were equally effective in increasing leaf Ca concentrations. This suggests that movement of Ca to leaf margins where localized Ca deficiency and tipburn occurs (Thibodeau and Minotti 1969) is more effectively achieved by low nutrient solution EC.

Tolerant lettuce cultivars are grown to minimize tipburn losses (Collier and Tibbitts 1982), although the choice is limited where fancy lettuce with particular characteristics such as the red pigmentation in cv. Red Mignonette are required. When the tipburn susceptibility of head lettuce cultivars was compared under tipburn conducive conditions in the experimental hydroponic unit used in the present study, susceptible cultivars suffered severe tipburn damage whereas Fame suffered little damage (Huett, unpublished data). Fame is accepted commercially as a tipburn tolerant cultivar and is widely grown during summer. The youngest leaves which contain the lowest Ca concentrations are the most susceptible to tipburn (Thibodeau and Minotti 1969) and the value for cv. Fame was 5·9 compared with 2·5 g kg^{-1} for cv. Red Mignonette. The concentrations in recently matured leaves of both cultivars which were relatively tolerant to tipburn were 13 and 11 g kg^{-1} respectively, consistent with the higher concentrations in mature leaves recorded in other studies (Mason and Guttridge 1975; Collier and Huntington 1983; Barta and Tibbitts 1986). Creswell (1991) considered a leaf Ca concentration range of 2·6–3·8 g kg^{-1} marginal for tipburn because of the consistent presence of symptoms in young leaves at this concentration range. Similarly, the three youngest leaves of cv. Red Mignonette had a Ca concentration range of 1·7 to 3·2 g kg^{-1} with tipburn consistently present. These results confirm that leaf tissue Ca concentration is related to tipburn tolerance and may account for differences in cultivar tolerance.

Lettuce grown at an EC of 0·4 dS m^{-1} was N and K deficient (Piggott 1986; Huett and White 1992) and the final yield was reduced. An increase in EC to 1·0 dS m^{-1} eliminated nutrient deficiency in cv. Coolguard and both rapidly transpiring (YFEL) and slowly transpiring (head) leaves contained the highest Ca concentrations compared with other ECs. The present study demonstrated that the commercial practice of growing lettuce in recirculating nutrient solution culture at an EC of 2·0–2·5 dS m^{-1} is detrimental to yield and renders plants susceptible to tipburn. An EC of 1·6 dS m^{-1} generally produced the highest yield of all cultivars, although the risk of tipburn can be substantially reduced with little reduction in yield by growing lettuce at an EC of 1·0 dS m^{-1}. Where susceptible cultivars such as Red Mignonette are being grown, at the expense of a 25% yield reduction, tipburn severity can be reduced by 50% by growing plants at an EC of $0 \cdot 4$ dS m^{-1}.

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