Title: Potassium fertility management for optimum tomato yield and fruit color

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Executive summary:

Potassium is a critical nutrient for processing tomato production; high yield, high quality production requires plant uptake of more than 300 lb K/acre. Providing sufficient soil K availability for maximum yield and fruit quality is difficult in many field situations; the growth habit of determinate processing varieties, high soil K fixation potential, and competing ion effects can all limit K uptake. Fertigation through buried drip irrigation offers the potential for more efficient K fertilization. The objectives of this project were to compare the effects of continuous and periodic K fertigation strategies on yield and fruit quality of drip-irrigated processing tomatoes under representative commercial field conditions, and to examine K availability dynamics in a range of Central Valley soils.

K fertigation trials were conducted in commercial fields near Winters and Woodland in Yolo County in 2004. At each site two fertigation strategies were tested: continuous fertigation with 100 PPM K, and 5 weekly injections of 40 lb K/acre. Both treatments were initiated during early fruit set; weekly applications ended 4 weeks later, and the continuous fertigation was terminated when a seasonal total of 200 lb K/acre had been applied. These treatments were compared to the grower management practice, which included no in-season K application. Plots were machine harvested, and detailed fruit quality analysis was performed.

K fertigation had significant effects on leaf and petiole K concentration at both sites, with larger differences observed at Woodland; compared to current leaf K concentration norms for high yield conditions, the grower treatment in both fields was K- limited. Neither the continuous nor the weekly K fertigation method was consistently superior. There was a trend toward higher fruit yield, soluble solids concentration and brix yield with both K fertigation treatments at Winters, but those trends were not statistically significant. At Woodland both K fertigation methods significantly increased total and marketable fruit yield, resulting in higher

brix yields. K fertigation improved fruit color at both sites. At Winters a surprisingly low incidence of the fruit color disorder yellow shoulder (YS) was observed (only 4% of fruit affected in the no K grower treatment), and although K fertigation numerically reduced YS incidence the reduction was not significant. However, the color characteristics L* and hue (which measure the lightness and intensity of the red color, respectively) were improved with K fertigation. YS incidence was higher overall at Woodland, with no significant treatment differences. However, blended color, L* and hue were all improved by fertigation, with continuous fertigation being marginally more effective than weekly application. At Winters the trend toward higher fruit K concentration with fertigation was not significant, while at Woodland both fertigation methods were equally effective at increasing fruit K.

Greenhouse studies were conducted examining K bioavailability dynamics in 8 representative Central Valley soils varying widely in exchangeable K. Plastic columns of either 20 cm (8 inch) or 1.5 cm height were packed with these soils and topped with a densely woven nylon fabric. Pre-germinated fescue seeds were place atop the fabric and grown for 2 weeks; the fabric allowed root hairs, but not roots, to penetrate into the soil, creating a two-dimensional soil/root interface. Fescue K uptake and soil K dynamics were documented for three K fertility treatments: blending K fertilizer into the soil at the rate of 100 PPM (dry soil wt basis) before the experiment; watering the columns (from the bottom, by capillarity) with 100 PPM K solution during the experiment; or adding no K.

In all soils and all K treatments fescue K uptake occurred predominately from the top 2 mm of soil (the portion of the soil in intimate contact with root hairs); this demonstrated the extremely limited diffusive K movement in soils. Blending K into dry soils increased fescue K uptake by an average of 43%. Watering with K in solution had minimal effect on fescue K uptake in the 20 cm columns, while in the 1.5 cm columns K uptake was increased > 300%; this suggested that the effective limit of K movement (by a combination of diffusion and mass flow) from the point of application is between these heights. The dramatic increase in K uptake in the solution K treatment in the 1.5 cm columns, compared to the more modest effect of dry soil amendment, illustrated the potential for effective K fertigation.

Introduction:

The California processing tomato industry has traditionally focused on the production of bulk paste, for which the main fruit quality issues are overall color and soluble solids content. However, in the past decade changes in the marketplace (increasing sales of salsa and 'chunky' sauces, for example) have dramatically increased the need for whole peeled, or peeled and diced, fruit. A primary quality criterion for peeled fruit is color uniformity. Uneven ripening of processing tomatoes is a common problem in California. The typical external symptom is a ring of tissue around the stem scar that remains yellow even after fully ripe. This symptom, called 'yellow shoulder' (YS), can range widely in severity; when peeled, the discolored area is invariably larger than was evident externally. YS occurs at a sufficiently high frequency to render whole fields unsuitable for peeling. There is a distinct geographical distribution of this disorder, with the Sacramento Valley much more severely affected than the Westside of the San Joaquin Valley.

Potassium nutrition has been conclusively linked to tomato fruit color. In a survey of 140 commercial fields throughout central California, Hartz et al. (1999) found that the incidence of YS and internal discoloration was correlated with soil K supply and the level of exchangeable soil Mg. They suggested that YS could largely be avoided by selecting fields on the basis of K and Mg supply. Fields with exchangeable soil K > 250 PPM, and exchangeable Mg/K ratio < 12, are likely to have little or no color problem. Site selection for YS avoidance is feasible in the southern San Joaquin Valley because only a small minority of fields have soil cation characteristics conducive to YS development. However, in the Sacramento and northern San Joaquin Valleys the majority of fields are potentially problematic, and many growers have no fields with ideal characteristics; if they are to remain viable as tomato growers, effective and economically feasible YS control measures must be found.

Field trials using conventional (preplant or sidedress) soil applications have shown that K fertilization can suppress YS, but does not eliminate it (Hartz et al., 1999; Hartz et al., 2001). Fertilization rates in excess of 500 lb K/acre have proven insufficient to reduce YS incidence to acceptable levels in some problem fields. One reason for such disappointing results is that many California soils have high K fixation characteristics; Hartz et al. (2002) showed that as much as 80% of applied K can be fixed in interlayer sites in vermiculitic minerals. Also, K diffusion rates differ widely among soils (Miller, 1988), suggesting that placement of K fertilizer in relation to the active root zone may affect crop response. The very high rates of K fertilization required with conventional application techniques (preplant or sidedress) are economically impractical unless significant yield increase is also achieved. However, with conventional K application techniques, improved fruit yield has only been observed in fields with exchangeable soil K < 130 PPM (Hartz et al., 2001).

Another alternative K application technique would be K fertigation via drip irrigation. Since soil K fixation occurs predominately during the drying cycle following irrigation (as K becomes more concentrated in the remaining soil solution, Cassman et al., 1990), drip irrigation may minimize fixation by maintaining more uniform soil moisture. Also, by repeatedly increasing the soil solution K concentration in the most active rooting zone, K movement to active root surfaces may be significantly enhanced. Drip irrigation has been used intermittently on processing tomatoes in California for two decades, but in recent years the acreage and number of growers involved has increased substantially, and continues to grow.

This project was undertaken to investigate the relative effectiveness of continuous and periodic K fertigation strategies on drip-irrigated tomato yield and fruit quality. Furthermore, K availability dynamics in a range of Central Valley soils was also investigated.

Objectives:

a) Compare the effects of continuous and periodic K fertigation strategies on yield and fruit quality of drip-irrigated processing tomatoes under representative commercial field conditions.

b) Examine K availability dynamics in a range of Central Valley soils.

Methods:

Field studies:

Trials were conducted in drip-irrigated commercial fields near Winters and Woodland in Yolo County. The soil at both sites was a Capay silty clay, with intermediate K supply and high exchangeable Mg. Soil characteristics (top 12 inch sample) and cultural details are given in Table 1. Both sites had a history of YS occurrence. Two K fertigation treatments were overlayed on the cooperating grower's fertigation treatment:

1) continuous K fertigation at 100 PPM K
2) 5 weekly fertigations of 40 lb/acre K each

The continuous fertigation treatment began on May 23 and May 26 at the Winters and Woodland sites, respectively; crop growth stage in both fields was early fruit set. This application timing was chosen based on prior experimentation showing yield response to K fertigation to be most likely if applied during fruit set (T.K. Hartz, unpublished data), and research by Francis et al. (2000) documenting that YS develops early in fruit development. Continuous fertigation was discontinued after a seasonal total of 200 lb K/acre had been applied; this occurred on June 30 at Winters, with the crop at about 20% red fruit. K fertigation was terminated at the Woodland site on June 28, at which time the first fruits were ripening. In the weekly fertigation treatment K was applied once per week for 5 consecutive weeks, for a seasonal application of 200 lb K/acre. Weekly fertigation began on May 21 at the Winters site June 3 at Woodland.

KCl solution (0-0-12) was used for both fertigation treatments. For each fertigation treatment a pump operated by a pressure-sensitive switch (which turned on when the irrigation system was pressurized) pumped the KCl into the irrigation stream of individual drip lines; in this manner all plots received the same amount of water and fertilizer applied by the grower; the only difference was the addition of KCl in selected plots. A randomized complete block experimental design with 6 replications was used at both sites, comparing the K fertigation treatments with a control treatment receiving no K fertigation; neither grower applied fertigated K. Individual plots were one row wide by either 300 ft (Woodland) or 1,300 ft long (Winters).

Leaf samples were collected just prior to the initiation of K fertigation and twice thereafter, roughly corresponding to three growth stages: early fruit set, full bloom, and early red fruit. Samples of whole leaves, and of petioles, were oven-dried, ground and analyzed for macro- and minor elements by standard laboratory procedures. At commercial maturity a 100 ft. section of the middle of each plot was machine harvested and weighed. Subsamples of fruit were collected and graded to determine the % of rejects by weight (green, sunburn, rot), allowing a calculation of marketable yield. Samples of marketable fruit were delivered to a PTAB inspection station for analysis of soluble solids concentration (SSC) and blended color. Fifty red fruit per plot were evaluated visually for the occurrence of yellow shoulder; any fruit with a contiguous ring of yellow tissue at least 2 mm wide surrounding the stem scar was considered affected. On 25 randomly selected red fruit per plot the skin was removed from the shoulder region and the subskin color evaluated by a Minolta colorimeter. Two measurements per fruit were taken, with the L* and hue values recorded. L* rates the lightness of, and hue the intensity of, the red color. Additional whole, red fruit were oven-dried, ground and analyzed for K concentration.

Laboratory and greenhouse studies:

Soil samples (top 6 inches) were collected from 8 commercial fields (including the K fertigation trial sites) in the San Joaquin and Sacramento Valleys. Fields were chosen to represent a range of soil exchangeable K levels as well as a range of K intensity (exchangeable K as a % of base saturation, Table 2). In addition to the standard ammonium acetate extraction method of analysis to measure exchangeable cations, these soils were also evaluated for K fixation potential, K bioavailability, and cation concentration in soil solution.

K fixation potential was estimated using the procedure of Hartz et al. (2002), a modification of a procedure developed by Cassman et al. (1990). In brief, 3 g of air-dried soil was mixed with 3 ml of 1.0 mM KNO_3 (equivalent to 390 PPM K on a dry soil weight basis) and allowed to air-dry. The K-enriched soil and unenriched soil were extracted in 1.0 M NH_4Cl, and the K concentration determined. The % of applied K not recovered in the extraction was considered to have been fixed within soil particles, and not readily available for plant uptake.

K bioavailability was characterized using a modification of the cation exchange membrane technique of Qian et al. (1996). Chelating membrane disks (Empore™ 3M, St. Paul, Mn) with a reactive area of 17 cm^2 were twice eluted in 0.5 M $NaHCO_3$, and then rinsed with deionized water. A pressure plate apparatus was used to bring all soils to their respective gravimetric water content at field capacity. Approximately 10 mm thickness of moist soil was compressed on top of the membrane in a beaker to ensure complete contact with the reactive surface. Samples were incubated at 68^o F for 16 hr. The membranes were removed, rinsed with deionized water to remove adhering soil particles, then eluted in 40 ml 0.5 M HCl for one hr to remove adsorbed K. The extract was analyzed for soluble K by atomic emission spectrometry. There were 3 replicate measurements per soil sample.

Soil solution cation concentration was determined by an acetone extraction procedure. Moist soil of known gravimetric water content and acetone were combined and shaken; the mixture was then filtered to obtain a clear liquid solution containing both acetone and soil water (water and acetone are highly miscible). This solution was then evaporated, leaving only the salts contained in the soil water. These salts were redissolved into 2% acetic acid and cation concentration was determined by atomic emission spectrometry. Cation concentration in the original soil solution was calculated based on the dilution factors inherent in the technique, and was corrected for the small amount of cations removed by acetone in an extraction of oven-dry soil samples.

The dynamics of K bioavailability, and the effectiveness of K enrichment techniques, were examined in greenhouse studies. In the initial study three K treatments were compared:

1) unamended soil receiving no liquid K
2) soil amended with 100 PPM K on a dry weight basis (from K_2SO_4) blended dry before initiation of the experiment
3) unamended soil enriched by 100 PPM K (from K_2SO_4) in the watering solution throughout the duration of the experiment.

Columns of soil from each field were constructed using bottomless polystyrene cups of approximately 20 cm (8 inch) height. The soil columns were placed on platforms over reservoirs of 0.01 M $CaCl_2$ solution, either with or without K; $CaCl_2$ was used to simulate the salt content of irrigation water. The columns were in contact with capillary matting, which extended into the reservoirs; the matting was used to wick solution from the reservoirs into the soil columns. Solution in the reservoirs was adjusted daily to maintain a set height differential between the solution level and the top of the columns to maintain a gravimetric water content at the top of the columns close to field capacity.

The experiment was arranged in a split-plot design within randomized complete blocks. The K treatments were the main-plot, with the eight field soils randomized within the K treatments as the split-plot. There were four replicate columns for each K treatment / soil combination, for a total of 96 soil columns.

After the initial soil wetting (by capillary action from the reservoirs) a layer of thin, 400 mesh nylon fabric was placed atop each column; 5 g of imbibed seeds of 'Bonzai' fescue (*Festuca arundinacea*) were placed on top of the fabric. The pores of the fabric were sufficiently small to prevent roots from penetrating into the soil, while allowing the penetration of root hairs, effectively creating a two-dimensional root interface. A layer of moist pea gravel was placed on top of the seed, and the columns were capped with aluminum foil until germination to minimize moisture loss. The greenhouse was maintained between 50-70% relative humidity, at a day and night temperature regime of 72^o F and 68^o F, respectively.

The experiment was terminated 14 days after sowing. All plant tissue per column (including the roots that had developed on the nylon fabric) was oven-dried and the dry weight recorded. Dry plant samples were ground to pass a 0.5 mm screen, and analyzed for K concentration following 2% acetic acid extraction. Moist soil was collected at three sampling depths (0-2 mm, 4-6 mm and 10-12 mm from the top of the soil column) and evaluated for K status. A portion of each sample was extracted using the acetone procedure previously described, and the soil solution cation concentration determined. Another portion of each sample was air-dried, ground, and extracted with 1.0 M ammonium acetate to measure exchangeable cations.

A second greenhouse experiment was conducted using a soil column height of only 1.5 cm, compared to 20 cm in the initial study. The height of the capillary matting was increased so that the soil at the top of the columns remained close to field capacity moisture content. The experimental procedure was repeated, with these changes:

a) only 3 of the 8 soils were used (chosen to represent low, medium and high K availability)
b) only two K treatments were compared: unamended soil wetted with 0.01 M $CaCl_2$, and unamended soil wetted with 0.01 M $CaCl_2$ 100 PPM K.

The experiment ran for 17 days, at which time the fescue tissue was harvested, dried and analyzed for K content. The top 2 mm of soil from the columns was air-dried and analyzed for exchangeable K.

Results:

Field studies:

K fertigation had a significant effect on tissue K concentration at both sites, with larger differences observed at Woodland (Tables 3 and 4). Compared to whole leaf K concentration norms for high yield conditions developed for processing tomatoes by Hartz et al. (1998), the grower (no K) treatment in both fields was K limited. The Winters site also had low and potentially yield-limiting tissue P concentrations. All other nutrients appeared to be in sufficient supply at both sites. Neither the continuous nor the weekly K fertigation method was consistently superior, with a trend toward higher tissue K with weekly fertigation at Winters, and the opposite trend at Woodland.

There was a trend toward higher marketable yield, SSC and brix yield at Winters, but these differences were not statistically significant at $p < 0.05$ (Table 5). At Woodland both K fertigation methods significantly increased total and marketable fruit yield, resulting in higher brix yields. K fertigation improved fruit color at both sites. At Winters a surprisingly low incidence of YS was observed (only 4% of fruit affected in the no K grower treatment), and although K fertigation numerically reduced YS incidence the reduction was not significant. However, both the color characteristics L* and hue were improved with fertigation, while blended color was unaffected (*for all three color characteristics lower numerical values are desirable*). Overall YS incidence was higher at Woodland, with no treatment differences evident. However, blended color, L* and hue were all improved by fertigation, with continuous fertigation being marginally more effective. At Winters the trend toward higher fruit K concentration with fertigation was not significant, while at Woodland the fertigation methods were equally effective at increasing fruit K. Even with K fertigation, fruit K concentration remained low at both sites; Hartz et al. (1999) found fruit K concentration in processing tomato fields to be commonly in excess of 4%.

Based on soil characteristics the Winters site should have been more likely to be K deficient than the Woodland site. The lack of significant crop response to K fertigation at Winters may have been due to the potentially yield-limiting effects of very low plant P status. Variety may have played a role as well, through differential rooting, fruit set, and K translocation characteristics. Also, K fixation potential was greater at Winters (46% vs. 31% for Woodland), and K fertigation had a smaller impact on crop K status there.

At current fertilizer prices the K fertigation treatments tested would cost approximately $100/acre. To cover that cost growers would have to realize a yield advantage of 2-3 tons/acre, or a price premium for improved fruit color. Currently, processing tomato contracts generally do not contain financial incentives for fruit color. Averaging these trial results with similar K fertigation trials conducted at UC Davis in 2002 and 2003, yield increase alone would have recouped the fertilizer cost. It is important to note that all these fertigation trial sites had soil exchangeable K considerably greater than the 130 PPM threshold for likely yield response using conventional K application methods (preplant or sidedress soil applications, Hartz et al., 2001). Additional experimentation is required to determine if lower fertigation rates would be as effective. From the standpoint of soil fertility maintenance, the 200 lb K/ace fertigation rate employed in these trials was approximately equal to the typical K removal in harvested tomato fruit.

Laboratory and greenhouse studies:

The eight soils chosen for study ranged from 118 - 383 PPM exchangeable K, with K accounting for 1.1 - 4.7 % of base saturation (Table 2). K fixation potential ranged from 8 - 64% of applied K, and was negatively correlated with exchangeable K (r = - 0.83). While K bioavailability was correlated with exchangeable K (r = 0.72, Fig. 1), the correlation with K intensity (% of base saturation) was greater (r = 0.96, Fig. 2). The strength of these relationships suggest that the K bioavailability procedure (which is quite laborious) provides essentially the same information as standard ammonium acetate exchangeable cation analysis.

In the first greenhouse experiment fescue K uptake generally increased with increasing initial soil exchangeable K (Fig. 3). The low fescue uptake in the no K treatment of the Winters soil was at least partially due to seedling damping off and poor fescue growth apparently unrelated to soil K dynamics. Amending the soils with dry K before the experiment increased fescue K uptake substantially in all soils except the Robbins soil, which had the highest K fixation potential; across soils, dry K amendment increased fescue uptake by 43%. By contrast, applying K in the liquid solution had little effect, increasing fescue uptake across soils by only 10%.

In all soils and K treatments, soil exchangeable K was reduced substantially only in the 0-2 mm depth (the soil immediately adjacent to the root interface, Fig. 4). The exchangeable K remaining at the 4-6 mm soil depth was only marginally lower than that at 10-12 mm depth. The exchangeable K remaining in soil receiving K in solution was virtually identical at all depths to that in unamended soil, while soil amended with dry K before the experiment showed substantially higher exchangeable K levels at all depths.

Analysis of soil solution cation concentration (acetone extraction method) showed a decrease in soil solution K at the 0-2 mm depth of approximately the same magnitude as for exchangeable K (27% decrease in solution K from 10-12 mm to 0-2 mm, compared with a 31% decrease in exchangeable K over that distance, Table 6). However, soil solution concentration of other cations (Ca, Mg and Na) increased dramatically at 0-2 mm depth (the result of plant transpiration-driven mass flow), drastically reducing K as a percentage of cations in solution. Averaged across soils, K constituted only 0.22% of cations in soil solution at the 0-2 mm depth. Soil columns wetted with 100 PPM K had very similar soil solution cation composition as columns receiving no K. Soil columns that had been amended with K before the experiment showed higher K availability at all depths, but the pattern of soil solution K depletion by depth was nearly identical to that seen in the unamended columns.

In the second greenhouse experiment using soil columns of only 1.5 cm height the results were quite different (Fig. 5). Adding 100 PPM K to the wetting solution more than doubled fescue K uptake in all soils, with the increase averaging 306% across soils. In the solution K treatment fescue K uptake was similar across soils, suggesting that the soil K availability limitation evident in the unamended Dos Palos and Woodland soils
was completely overcome. In the 100 PPM solution K treatment soil exchangeable K in the 0-2 mm depth in all soils was substantially higher (by an average of 180%) at the termination of the experiment than at the beginning, while the unamended soils showed the reduction in exchangeable K seen in the first experiment; this indicated that K movement through the short columns substantially exceeded fescue uptake.

The fact that, in all soils and K treatments in the first experiment, soil exchangeable K was substantially affected by fescue uptake only at the 0-2 mm depth suggested that effective K diffusion was extremely limited across soils. The marginal effect of the 100 PPM solution K treatment on fescue K uptake and soil exchangeable K at the top of the soil columns suggested that 20 cm (8 inches) exceeded the effective limit of K movement, either by diffusion or mass flow with transpirational water movement. The second experiment, using 1.5 cm soil columns, demonstrated that substantial K movement does occur over shorter distances in soil. Additional studies would be needed to document the effective limit of fertigated K movement, but these results suggested that the limit is less than 8 inches from the point of injection in typical Central Valley soils. However, in drip-irrigated culture maximum rooting density is within inches of the drip tape.

The laboratory and greenhouse studies help to explain the tomato fertilization trial results obtained over the last decade. When K fertilizer is conventionally applied (by preplant broadcasting, sidedress banding, or injection into furrow irrigation water) crop uptake of the applied K can be limited by K fixation (stimulated by multiple wetting and drying cycles) or placement distance from the concentrated root zone. Multiple fertigations through drip irrigation can overcome some of these limitations, providing a greater likelihood of yield increase, and more reliable fruit color improvement.

Outreach activities:

A field day was held at the Woodland trial site on July 28; approximately 25 industry personnel attended. In addition to a presentation of results at the FREP Conference in Tulare on November 9, the results of this project were presented at the Processing Tomato Roundtable in Napa on October 25 (40 attendees), a grower meeting in Modesto on December 8 (sponsored by the CTGA, attendance approximately 90), a grower meeting in Camarillo on December 15 (attendance approximately 35), and a grower meeting in Woodland on January 6, 2005 (attendance approximately 170). A summary article on potassium management in processing tomatoes has been written and submitted to the California Tomato Growers Association for publication in their magazine.

Table 1. Soil exchangeable cation characteristics and cultural details for the field sites.

	Field site	
Parameter	Winters	Woodland
Exchangeable soil K (PPM)	187	273
K (meq/100 g)	0.48	0.70
Ca (meq/100 g)	15.7	14.0
Mg (meq/100 g)	10.6	13.7
Variety	Heinz 2601	Heinz 9780
Transplanting date	March 18	April 16
Harvest date	July 30	August 23
Grower seasonal fertility program (lb/acre)		
N	192	249
P	42	31
K	105	0

Table 2. Soil texture and K status of the soils used in the greenhouse experiments.

	Exchangeable K				Particle size distribution (%)		
Field location	(PPM)	(meq/100 g)	(% of base exchange)	K fixation potential (%)	sand	silt	clay
Dos Palos	118	0.30	1.1	55	43	32	25
Winters	160	0.41	1.6	46	21	40	39
Robbins	204	0.52	1.2	64	11	31	58
Tracy	224	0.57	2.9	32	45	29	26
Colusa	231	0.59	4.4	24	55	29	16
Woodland	273	0.70	2.4	31	23	42	35
Five Points	339	0.86	2.7	8	28	39	33
Davis	383	0.98	4.7	15	30	47	23

Table 3. Effect of K fertigation treatment on whole leaf total nutrient concentrations.

		% in dry tissue						PPM in dry tissue				
Date	K treatment	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
							Winters					
May 21	No K	4.6	0.26	2.3	3.1	1.2	0.56	70	26	466	86	32
	Sufficiency minimum[z]	4.6	0.32	2.2	1.9	1.0	0.50					
June 11	No K	4.5	0.22	1.4 b	2.9	1.0	0.58	104	28	237	104	21
	Continuous K	4.5	0.23	1.4 b	3.0	1.0	0.59	106	29	242	97	20
	Weekly K	4.5	0.23	1.6 a	2.8	1.0	0.57	93	28	286	103	22
	Sufficiency minimum	3.5	0.25	1.6	1.8		0.50					
June 29	No K	3.2	0.16	0.7 b	4.8	1.8	0.84	175	27	430	131	19
	Continuous K	3.3	0.16	0.8 a	4.8	1.7	0.91	183	28	341	112	17
	Weekly K	3.3	0.16	0.8 a	4.7	1.7	0.92	171	27	382	124	19
	Sufficiency minimum	2.7	0.23	0.8	2.4	1.0	0.70					
							Woodland					
May 18	No K	5.2	0.46	1.8	3.0	1.7	0.79	98	13	603	131	28
	Sufficiency minimum	4.6	0.32	2.2	1.9	1.0	0.50					
June 23	No K	5.0	0.34	1.7 b	2.4	1.4	0.60	126	15	240	77	21
	Continuous K	5.1	0.36	2.3 a	2.1	1.2	0.61	114	14	196	71	22
	Weekly K	5.2	0.36	2.2 a	2.2	1.2	0.61	115	15	201	72	22
	Sufficiency minimum	3.5	0.25	1.6	1.8		0.50					
July 7	No K	4.4	0.28	1.1 b	2.5	1.4	0.66	137	13	241	79	17
	Continuous K	4.5	0.29	2.0 a	2.3	1.3	0.73	127	12	220	78	18
	Weekly K	4.6	0.30	1.8 a	2.3	1.3	0.73	132	13	238	78	18
	Sufficiency minimum	2.7	0.23	0.8	2.4	1.0	0.70					

z adapted from Hartz et al., 1998

means (within sites and dates) followed by different letters are significantly different at $p < 0.05$

Table 4. Effect of K fertigation treatment on petiole nutrient concentration.

Date	K treatment	NO_3-N (PPM)	K (%)	PO_4-P (PPM)
Winters				
May 21	No K	7,840	3.7	1,790
June 11	No K	4,330	3.0 b	690
	Continuous K	4,800	3.4 ab	810
	Weekly K	4,360	4.0 a	760
June 29	No K	140	0.6 b	550
	Continuous K	110	0.8 a	610
	Weekly K	110	0.9 a	610
Woodland				
May 18	No K	7,880	3.3	4,520
June 23	No K	5,470	2.6 b	1,680
	Continuous K	6,650	3.5 a	1,920
	Weekly K	6,570	3.5 a	1,960
July 7	No K	2,440	1.3 b	1,240
	Continuous K	3,560	3.5 a	1,480
	Weekly K	3,680	3.3 a	1,500

means (within sites and dates) followed by different letters are significantly different at $p < 0.05$

Table 5. Effect of K fertigation on fruit yield, soluble solids concentration, and color quality, 2004.

	Fruit yield (tons/acre)		Soluble solids	Brix yield	Color parameters				Fruit K
K treatment	Total	Mkt.	(°brix)	(tons/acre)	Blended color	% YS	L*	Hue	(% dw)
Winters									
Grower	41	39	4.58	1.88	25.5	4	45.2 a	55.3 a	3.5
Weekly	43	41	4.72	2.04	25.2	2	43.5 b	51.1 b	3.8
Continuous	41	40	4.78	1.98	25.0	2	43.5 b	50.9 b	3.7
Woodland									
Grower	52 b	49 b	4.42	2.15 b	27.7 a	11	45.9 a	49.8 a	3.1 b
Weekly	57 a	54 a	4.50	2.42 a	26.5 b	15	44.8 b	47.5 ab	3.6 a
Continuous	59 a	56 a	4.55	2.53 a	26.0 b	16	43.8 c	46.3 b	3.6 a

means (within sites) followed by different letters are significantly different at $p < 0.05$
for all color characteristics lower numerical values are desirable

Table 6. Soil solution cation composition at the termination of greenhouse experiment #1 (20 cm soil columns); mean of eight soils.

K treatment	Soil depth (mm)	Cation in soil solution (meq liter^{-1}) K	Ca	Mg	Na	% K (meq basis)
No K	0-2	0.19	37.5	35.9	14.1	0.22
	4-6	0.26	14.7	11.5	8.8	0.74
	10-12	0.30	10.8	7.5	7.6	1.15
Liquid K	0-2	0.20	31.1	28.6	13.3	0.27
	4-6	0.25	13.5	10.1	7.8	0.79
	10-12	0.29	9.3	6.7	6.7	1.26
Soil K	0-2	0.26	37.0	37.5	13.3	0.30
	4-6	0.35	15.1	11.4	8.2	1.00
	10-12	0.40	9.9	6.8	7.0	1.66

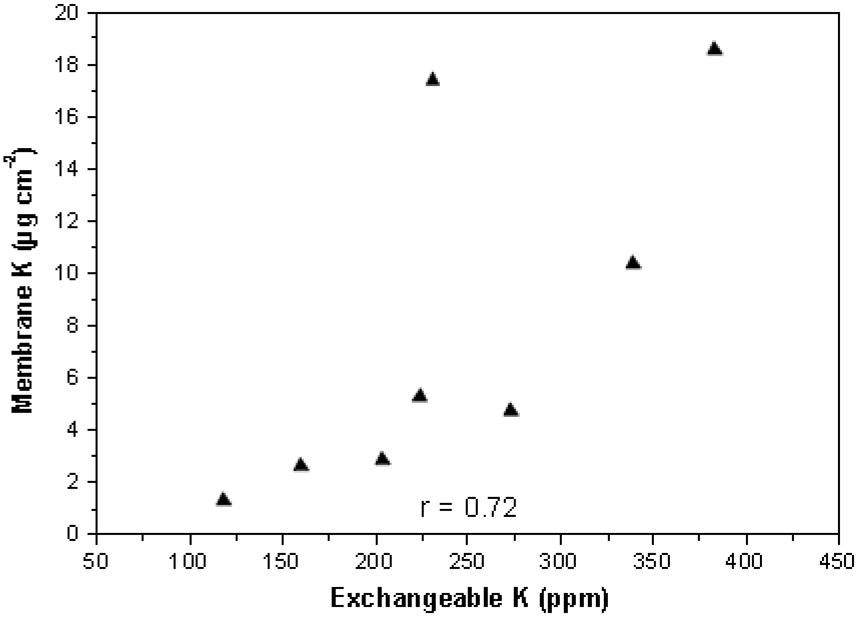

Fig.1. Relationship between cation membrane K and exchangeable K.

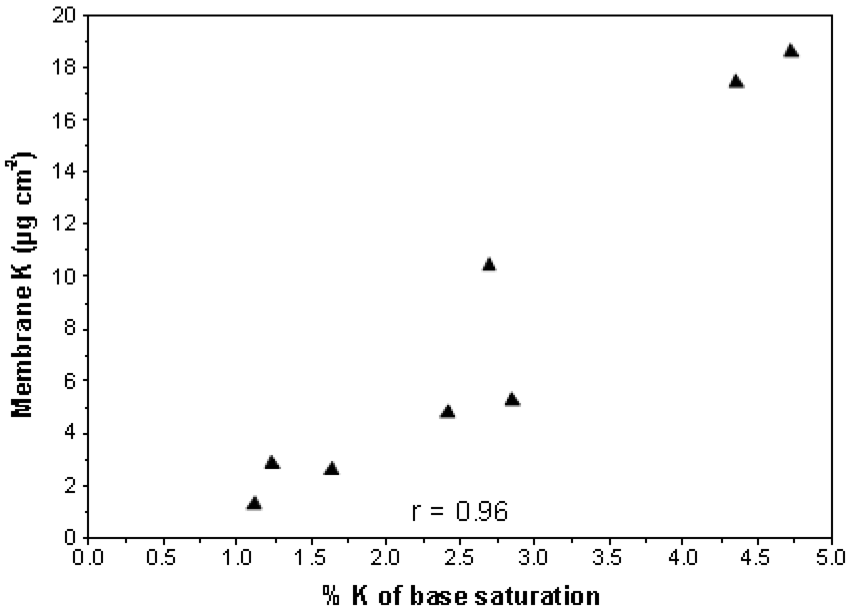

Fig.2. Relationship between cation membrane K and exchangeable K as a % of base saturation.

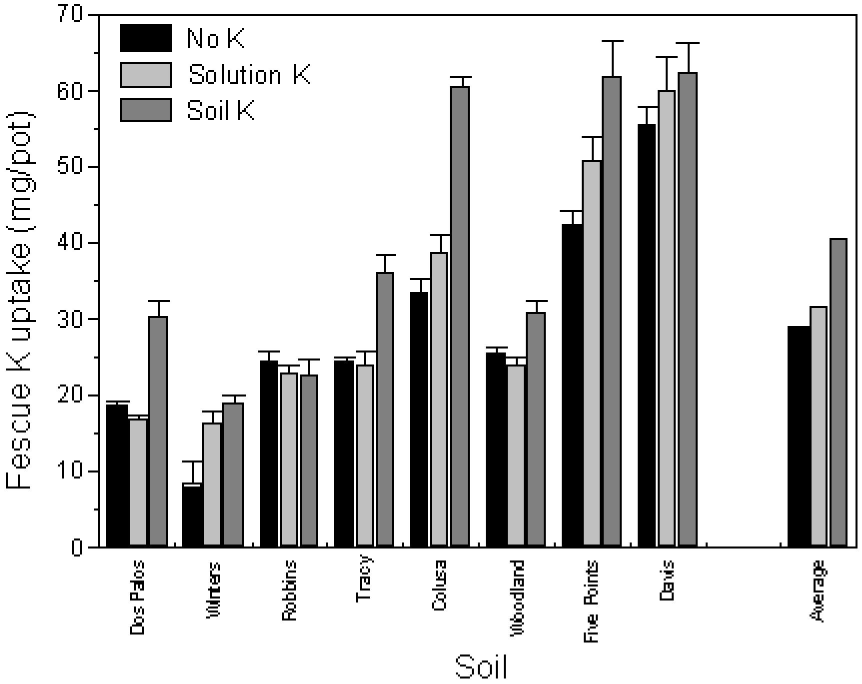

Fig.3. Effect of K treatment on total K uptake in fescue tissue (20 cm soil columns); bars indicate standard error.

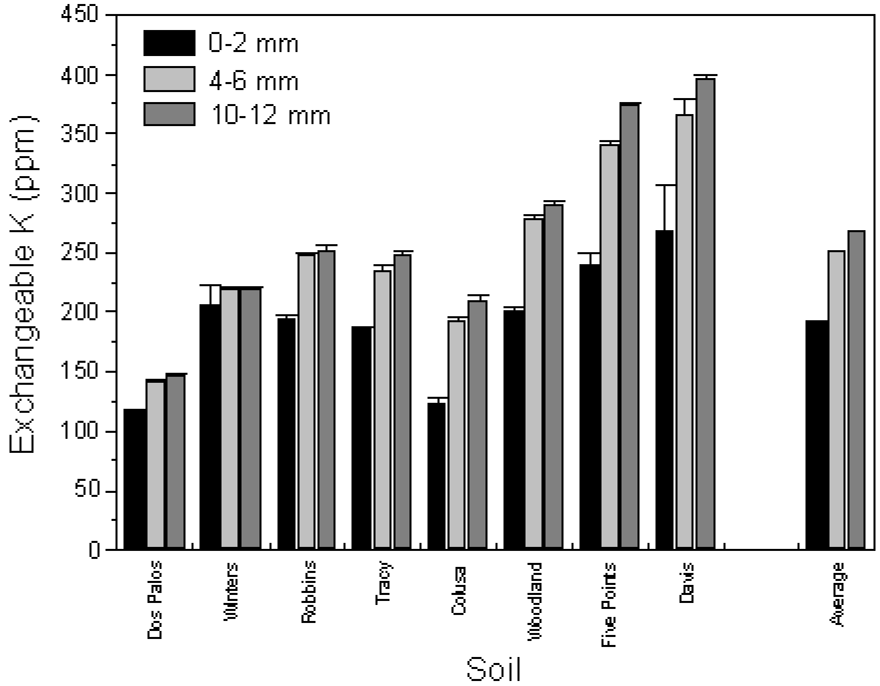

Fig.4. Effect of fescue K uptake on soil exchangeable K, by distance from the root/soil interface (20 cm soil columns); bars indicate standard error.

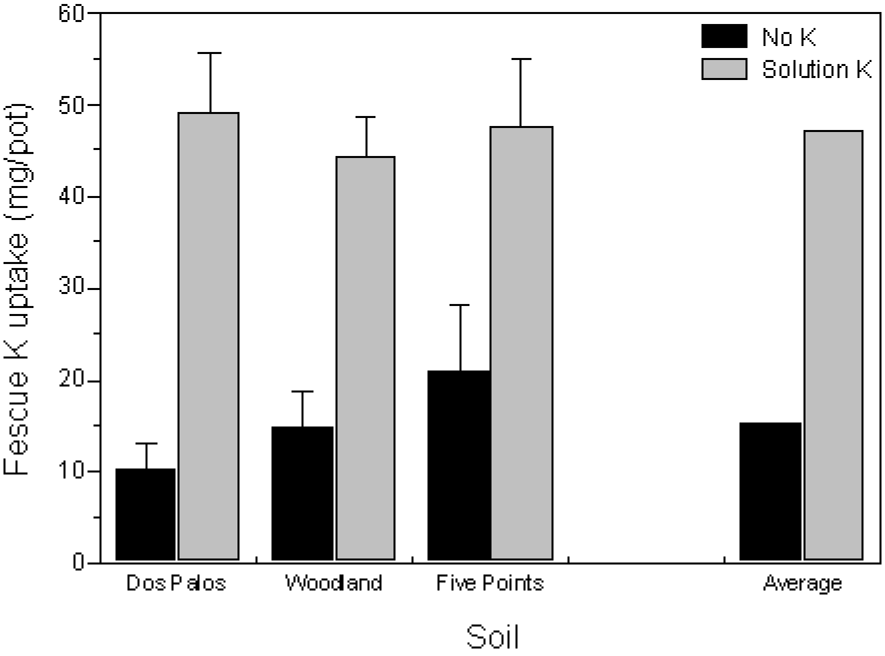

Fig.5. Effect of K treatment on total K uptake in fescue tissue (1.5 cm soil columns); bars indicate standard error.

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