NITROGEN AND POTASSIUM FERTILIZATION OF POTATOES: SUGARS AND STARCH[1]

D. T. Westermann, D. W. James, T. A. Tindall, and R. L. Hurst[2]

Abstract

Considerable evidence exists that both N and K influence potato (*Solanum tuberosum* L.) yields and quality. The impact of nutrients on tuber quality parameters under field conditions should be identified so optimum management practices can be utilized. We evaluated the N and K fertilization by K-sources effects on concentrations of nutrients, reducing sugars, sucrose and starch in the stem and apical tuber ends from two irrigated field experiments with the Russet Burbank cultivar. Nitrogen rates of 0, 112, 224 or 336 kg ha^{-1} were combined with selected K rates of 0, 112, 224 or 448 kg ha^{-1} as either KCl or K_2SO_4 arranged as an incomplete factorial. A multiple linear regression model was fit to the data and used to predict the response surface for a complete factorial for each K-source. Nitrogen applications increased or decreased reducing sugars in the apical and stem ends, respectively. Potassium decreased reducing sugars in both tuber ends. Sucrose was higher in the apical end than in the stem end but was not appreciably affected by fertilizer treatment. Nitrogen and potassium applications reduced dry matter and starch concentrations in both tuber ends. Potassium had a smaller effect on the apical end when starch was expressed on a dry weight basis, indicating that increased water content was a factor in the K effect. Both N and K concentrations in the tuber ends were negatively related to starch concentrations, but the relationship was different for the apical and stem ends. Tuber Cl concentration indirectly affected starch concentrations in the stem end when KCL was applied. The K fertilization effect on specific gravity depended upon the K concentration in the harvested tuber and was independent of K fertilizer source. These data illustrate the effects of preplant N and K fertilization rates on final tuber quality parameters. Additional studies are needed to further define the effects of nutrient concentrations at different plant growth stages.

Compendio

Existe considerable evidencia que tanto el N como el K influencian los rendimientos y calidad de la papa (*Solanum tuberosum* L.). El impacto de los nutrientes sobre los parámetros de calidad de la papa, bajo condiciones de

[1]Contribution from the USDA-ARS and the Utah Agric. Expt. Station, Logan, UT.

[2]Soil Scientist, USDA-ARS, Kimberly, ID 83341; Professor and Extension Specialist, Utah State Univ., Logan, UT 84322-4820; Extension Soil Scientist, Univ. of Idaho, Twin Falls, ID 83301; Professor Emeritus, Applied Statistics, Utah State Univ., Logan, UT 84322-4820, respectively.

Accepted for publication: January 14, 1994.

ADDITIONAL KEY WORDS: Apical end, stem end, sucrose, reducing sugars, chloride, tuber dry matter, sulfur, nutrients, potassium source.

campo, debe ser identificado de modo que pueden utilizarse prácticas óptimas de manejo. Se evaluó la fertilización con N y K por los efectos de las fuentes de K sobre la concentración de nutrientes, los azúcares reductores, sucrosa y almidón en los extremos apical y terminal de tubérculos de dos experimentos de campo bajo irrigación, con el cultivar Russet Burbank. Se combinaron dosis de 0, 112, 224, o 336 kg ha^{-1} de N, con dosis seleccionadas de K de 0, 112, 224 o 448 kg ha^{-1}, sea como KCl o como K_2SO_4, dispuestas como un factorial incompleto. Se dispuso la información convenientemente en un modelo de regresión linear múltiple y se le utilizó para pronosticar la superficie de respuesta para un factorial completo para cada fuente de K. Las aplicaciones de N incrementaron o disminuyeron los azúcares reductores en los extremos apical y terminal, respectivamente. El K redujo los azúcares reductores en ambos extremos del tubérculo. La sucrosa fue más alta en el extremo apical que en el terminal, pero no fue apreciablemente afectada por el tratamiento con fertilizantes. Las aplicaciones de N y K redujeron las concentraciones de materia seca y almidón en ambos extremos del tubérculo. El K tuvo un efecto menor sobre el extremo apical cuando se expresó el almidón en base al peso seco, indicando que el incremento de contenido de agua era un factor en el efecto del K. Tanto las concentraciones del N como las del K, en los extremos del tubérculo, estuvieron relacionadas negativamente a las concentraciones de almidón, pero la relación fue diferente para los extremos apical y terminal. Cuando se aplicó KCl las concentraciones de Cl en el tubérculo afectaron indirectamente las concentraciones de almidón en el extremo terminal. El efecto de la fertilización con K sobre la gravedad específica dependió de la concentración de K en el tubérculo cosechado y fue independiente de la fuente de fertilizante potásico. Estos datos ilustran los efectos de las dosis de fertilización con N y K, aplicadas previamente al sembrío, sobre los parámetros de calidad final de los tubérculos. Se requieren estudios adicionales para definir aún más los efectos de las concentraciones de nutrients a diferentes estados de crecimiento de las plantas.

Introduction

Tuber quality can refer to total dry matter or starch content, reducing sugar content, flesh color, texture, mealiness, flavor, nutritional value and external tuber shape and size. The relative importance of each depends upon the intended tuber use. Dry matter content is an important characteristic of tubers used for processing into chips and french fries. Reducing sugars (*i.e.* glucose and fructose) also influence processing because of the Maillard reaction between the reducing sugars and amino acids upon frying. Dry matter and reducing sugars are related to tuber maturity, growing conditions, and water and nutrient uptake by the growing crop (6).

Both N and K availabilities influence tuber dry matter. Large to excessive amounts of available N stimulate top growth and delays tuber formation and maturity. Tubers harvested relatively immature will have a lower dry matter content. In addition, high N plants are more susceptible to secondary tuber growth problems. Generally, K reduces dry matter, with KCl having a greater effect than K_2SO_4 (26). However, both N and K applications can increase dry matter if there is a yield response from their application. The specific response to combinations of N and K fertilizer is also partially dependent upon variety and field environment (27).

Fertilizer rates influence reducing sugar accumulation (15, 18). Nitrogen appears to be indirectly related because of its effect on dry matter and relative maturity of the harvested tuber. Generally, K applications decrease reducing sugar and lighten chip color if yields increase (8, 14, 29). Plants adequately fertilized with N had tubers with lower reducing sugar concentrations at harvest and accumulated less reducing sugars during storage (15). The stem end of the tuber had more reducing sugars than the apical end and the difference was greater in the low fertilized treatment (15).

No relationships were found between the Ca, Mg, K and P concentrations and reducing sugar accumulation in apical or stem portions of Russet Burbank tubers (30). Inorganic P was positively correlated with the reducing sugar concentration in the stem portion of the tuber. Starch synthesizing enzymes have a specific requirement for K (24) and tubers depend upon a dynamic supply of K for highest starch content (19). About 1.8% K in the tuber dry matter is necessary for high starch concentrations but higher K concentrations tend to decrease starch concentrations (10). Starch on a fresh weight basis was positively correlated to K but negatively correlated on a dry weight basis when tuber K concentrations were higher than 1.8% K (22). Potassium was slightly higher in the apical than in the stem portion of the tuber (30, 31). In an earlier review, Harrap (1960) reported that high Cl concentrations decreased reducing sugars while total carbohydrates remained constant. He concluded that overall starch yield was probably related more to the amount of K uptake than to specific effects of Cl on the tuber's metabolism.

Potassium expedites the transport of carbohydrate from the leaves to the tubers (4, 12). With adequate K, over two-thirds of ^{14}C-labelled photosynthate moved from the leaves into the tubers within 24 h, while only half was translocated when K was deficient. Plants treated with K_2SO_4 translocated almost twice the photosynthate from the leaves and stems to the tubers compared with plants treated with KCl (11). Higher shoot:tuber ratios were found for plants treated with KCl compared with K_2SO_4. The enhanced shoot growth was attributed to a more negative solute potential and higher leaf water content in the KCl treated plants (5). This implies that K_2SO_4 stimulates phloem loading and translocation of assimilates more than KCl. Chloride functions as an osmoticum ion as well as an essential plant nutrient (9). Organic anions in the leaves and stems are also lower in the KCl treated plants.

Both K and N fertilization can influence tuber yield and quality. Inorganic nutrient interactions occur at the soil-root interface and within plant cells. These also include interactions with organic anions within the plant cell. Their effects on growth, partitioning of photosynthate to tubers or shoot, and sugar-starch metabolism in the tubers are complex and could influence processing quality. Many potato growers can intensively manage the nutritional status of the potato crop during production. The effect of nutritional management practices on tuber characteristics important for processing high quality potato products should be identified.

This research project evaluated the tuber yield and quality responses of Russet Burbank potatoes to N and K fertilization on a calcareous soil where environmental Cl and K concentrations were low. Other papers from this project discussed tuber yield and specific gravity effects (32) and selected petiole nutrient interactions (16). This paper presents the N and K fertilization by K-source effects on starch and reducing sugar concentrations, and dry matter in the apical and stem ends of the tuber.

Materials and Methods

General

Field experiments were conducted in 1988 and 1989 on a Millville silt loam soil (coarse, silty, carbonatic, mesic, typic Rendolls) near Logan, Utah. The soil and irrigation water at the sites, and the yearly operational procedures were described by Westermann *et al.* (1993). Soil test K concentrations were low and similar both years. Briefly, Russet Burbank seedpieces were planted the first week of May and the tubers harvested in late September after vine kill. Fertilizer materials (N and K) were banded 15 cm to the side of the seedpiece at planting. Both experiments were irrigated (surface, 1988; sprinkler, 1989). Tubers at harvest were visibly graded (2) and weighed. Specific gravity was determined on a composite subsample of U.S. #1 and #2 tubers (~5 kg) by the weight in water-weight in air method. After determining specific gravity, the tuber samples were placed in 15 C storage for later internal analyses.

Experimental Design

Both experiments were designed to specifically study the interactions between the independent (N and K) and dependent variables via response surfaces. Treatments were selected to define the optimum N and K fertilizer rates, *i.e.*, the central region of the response surface. Nitrogen and K treatment combinations were duplicated for two K-sources, KCl and K_2SO_4. Each experiment contained fourteen N and K fertilizer treatment combinations (Table 1) arranged as an incomplete factorial, replicated four times.

Tuber Chemical Analysis

Within 45 days after harvest, each tuber sample was removed from storage and warmed to room temperature(~25 C). A "constructed cutter" re-

TABLE 1.—*Fourteen treatment combinations in the incomplete N * K factorials for each K source.*[a]

K Source	K kg ha^{-1}	N rate, kg ha^{-1} 0	112	224	336
		Treatment number			
KCl	0	1	-	2	-
	112	-	3	-	4
	224	5	-	6	-
	336	-	-	-	-
	448	-	7	-	8
K_2SO_4	0	1	-	2	-
	112	-	9	-	10
	224	11	-	12	-
	336	-	-	-	-
	448	-	13	-	14

[a]Treatments 1 and 2 repeated in the K-source subsets for generating the respective response surface. The empty treatment cells in the incomplete factorial are represented a (-) and were estimated by a polynomial regression on the existing cells. Nitrogen applied as urea

moved a 1.25 cm "tip" from each end of each tuber and at the same time removed a 0.6 cm slice adjacent to the tip. Slices from the apical and stem tuber ends were processed separately and used to estimate the nutrient concentrations, dry matter, sugars and starch in the respective end of the tuber. Each slice was cut in half, one-half of which was placed in a Ziplock[3] plastic bag, weighed and frozen. Each sample was dried in a freeze-drier and then weighed to determine dry matter. Dried samples were pulverized in a blender and stored in snap-cap plastic vials in a freezer until extraction for sugar and starch analysis. A Yellow Springs Instrument Co. (YSI) Model 27 analyzer[3] (utilizing a glucose oxidase membrane and a modified phosphate buffer, pH 7.3) was used to determine sugars and starch after the appropriate extraction and conversions. If the analysis could not be completed within 2-4 h after preparation the samples were frozen. Two glucose standards, 200 and 500 mg dL^{-1}, were used to calibrate the analyzer and injected with a 25 µL syringe. These procedures were similar to those reported by Mazza (1983) for potatoes and by Budke (1984) for corn materials. Reducing sugar, sucrose and starch were determined and expressed in the tuber ends on a fresh and dry weight basis.

A 2.5 g dried tuber sample was vigorously shaken for 0.5 h with 50 ml 0.35 M phosphate buffer, pH 5.9, and then stored for 18 h at ~4 C. About 2 ml of this suspension was filtered through a Whatman GF/A glass microfibre

[3]The use of a name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

filter[3] into each of two 10 ml polypropylene culture tubes. One tube was used for dextrose analysis (reducing sugars), while 10 µL of an invertase solution (200 mg invertase per 2 ml deionized water; Sigma Chemical Co., I4504[3]) was added to the other tube and mixed. The second tube was incubated for 0.5 h at 40 C in a water bath. Dextrose was determined on the solution in both tubes with the YSI Analyzer (1). The dextrose concentration difference between the two tubes was used to calculate sucrose concentration in the tuber slices. An internal sucrose standard (Baker Analyzed Reagent, 4072-1[3]) was included in each sample set (20-40 samples) to determine recoveries.

Starch was determined by placing 0.25 g dried tuber sample into a 125 ml Erlenmeyer flask containing 40 ml deionized water. The flask was capped with aluminum foil and autoclaved for one hour at 120 C. After cooling, 5 ml of 1.0 N sodium acetate, pH 4.2, was added to each flask and mixed. Amyloglucosidase (1 ml of a 10% wt/wt in 0.7 M phosphate buffer, pH 5.9; Sigma Chemical Co. A7255[3]) was added, mixed, and the flask placed into a water bath at 40 C. After one hour, 2.5 ml of 25% trichloroacetic acid was added to each flask to precipitate protein and stop the enzymatic reactions. The contents of each flask were transferred to a 100 ml volumetric flask and brought to volume with 0.7 M phosphate buffer, pH 5.9. Three ml of this solution were transferred to a polypropylene tube and incubated in a water bath for 0.5 h at 40 C. After cooling this solution was frozen until analyzed for dextrose with the YSI Analyzer (3). The initial reducing sugar and sucrose was subtracted before calculating starch concentration. An internal starch standard (potato starch, Sigma Chemical Co., S2630[3]) was included in each sample set to determine recoveries.

Each dried tuber sample (0.5 g) was dry ashed for six hours at 500 C and the residue dissolved in 50 ml 0.2 N HNO_3. This solution was analyzed for Zn, Cu, Mn, Fe, K, Ca and Mg by atomic absorption spectrophotometry; and for Cl and S by flow injection analysis (Lachat Instrument[3], Milwaukee, WI., Methods #12-117-07-1-A and #12-116-10-1-C). Nitrogen and phosphorus were determined by flow injection analysis after Kjeldahl digestion (Lachat Instrument, Milwaukee, WI., Methods #13-107-06-2-A and #12-115-01-1-A). All elements were reported on a dry matter basis.

Statistical Procedures

Initially, a preliminary two-way analyses of variance (ANOVA) was calculated for each tuber variable, using treatments as one factor and the apical or stem (AS) tuber end as another factor. In addition, a separate ANOVA for each tuber end was calculated and where significant treatment effects occurred the treatment means were used to produce a multiple linear regression equation for the model: $Y = b_0 + b_1N + b_2K + b_3(Cl/SO_4) + b_4N^2 + b_5K^2 + b_6NK + b_7N(Cl/SO_4) + b_8K(Cl/SO_4) + b_9N^2(Cl/SO_4) + b_{10}K^2(CL/SO_4) + b_{11}NK(CL/SO_4)$, where Cl/SO_4 is represented as a categorical variable in the model as

+1 or -1, respectively. Treatments 1 (0 N, 0 K) and 2 (224 N, 0 K) were duplicated in each K-source subset. The regression equation estimated all cell values (response surface) for a complete factorial (4N x 5K x 2K-sources). The multiple linear regression model was a subdivision of the treatment degrees of freedom within each tuber end ANOVA. The coefficient of multiple correlation, R^2, between the measured and estimated treatment means was computed. Response surfaces were chosen for illustrating and interpreting the interactions encountered. In this method of presentation, the individual treatment means are less important than treatment trends and interactions. Stepwise and linear regression relationships were also estimated for selected tuber variables (23). The stepwise regression procedure used a F-ratio of 4.0 to select or reject a variable in deriving the final model.

Results

Yield and specific gravity responses to N and K fertilization, and K-sources were discussed by Westermann *et al.* (1993). Briefly, N and K applications increased tuber yields independent of K-source. Nitrogen decreased specific gravity. Each K-source decreased specific gravity a similar amount at a specific N rate. Without N, KCl reduced specific gravity but K_2SO_4 did not.

Significant treatment effects on tuber dry matter, reducing sugars, sucrose and starch were observed except for reducing sugars in 1989 (Table 2). The (treatment*AS) interaction was also significant (Pr>F @ 0.10) except for dry matter and reducing sugars-dry in 1989. The remaining sugar and starch data are presented on a fresh weight basis since chips and french fries are generally processed from fresh tubers.

TABLE 2.—*Analysis of variance: Treatment (Trt) and AS[a] effects on internal tuber sugars and starch.*

	1988			1989		
Variable[b]	Treatment	AS	Trt*AS	Treatment	AS	Trt*AS
	Pr>F					
Dry Matter	0.0001	0.4050	0.0001	0.0001	0.0003	0.3502
Reducing sugars-dry	0.0001	0.0001	0.0001	0.4346	0.0050	0.3946
Reducing sugars-fresh	0.0001	0.0001	0.0001	0.1058	0.0001	0.0008
Sucrose-dry	0.0001	0.0001	0.0001	0.0002	0.0001	0.0008
Sucrose-fresh	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Starch-dry	0.0001	0.5056	0.0644	0.0001	0.7589	0.0001
Starch-fresh	0.0001	0.8975	0.0001	0.0001	0.0089	0.0789

[a]AS = apical or stem end of tuber.

[b]Expressed on either a fresh or dry weight basis.

TABLE 3.—*Linear correlation coefficient*[a] *(r) between selected tuber quality variables for both tuber ends (1988 and 1989 data combined).*

Variable	Tuber end	Dry matter Apical	Dry matter Stem	Reducing sugar[b] Apical	Reducing sugar[b] Stem	Sucrose[b] Apical	Sucrose[b] Stem	Starch[b] Apical	Starch[b] Stem
Dry matter	Apical	1.00							
	Stem	0.38	1.00						
Reducing sugar[b]	Apical	0.66	0.02	1.00					
	Stem	0.90	0.16	0.62	1.00				
Sucrose[b]	Apical	-0.76	-0.15	-0.86	-0.68	1.00			
	Stem	-0.46	-0.35	-0.44	-0.31	0.51	1.00		
Starch[b]	Apical	0.99	0.42	0.64	0.90	-0.75	-0.44	1.00	
	Stem	0.54	0.96	0.10	0.36	-0.29	-0.42	0.57	1.00

[a]r = 0.35 and 0.45 for probability levels of 0.05 and 0.01 with 30 degrees of freedom, respectively.
[b]Expressed on a fresh weight basis.

Sucrose in the stem end was near detection limits both years (Data not shown). This may have partially been because sucrose was determined by the difference between the reducing sugar concentration before and after converting the sucrose to glucose and fructose with invertase. Sucrose concentrations (fresh wt) in the apical end were from 0.18 to 0.30% in 1988 but were all below 0.03% in 1989 (Data not shown). The apical end may have contained more sucrose than the stem end at harvest because of relative immaturity. Part of the differences between years might have been related to the furrow and sprinkler irrigation methods used in 1988 and 1989, respectively. Specific gravities were also lower in 1988 compared with 1989 (32).

Linear correlation coefficients between apical or stem ends for dry matter, reducing sugar, sucrose and starch were significant (Pr>F @ 0.05) but less than 0.63 (Table 3). All correlation coefficients between sucrose and dry matter or starch were negative, with those for the apical end about twice the stem end. Correlation coefficients between starch and dry matter within each tuber end were greater than 0.95. Specific gravity was also highly correlated to average tuber dry matter or starch, r = 0.93 and 0.94, respectively (Data not shown). The relationship between dry matter and specific gravity in tubers is well known (2, 28).

All R^2 for the multiple linear regression equation were highly significant (Table 4). The lowest standard error (SE) was for the estimated mean of the 224 kg ha^{-1} N and 112 kg ha^{-1} K treatment for all variables, while the

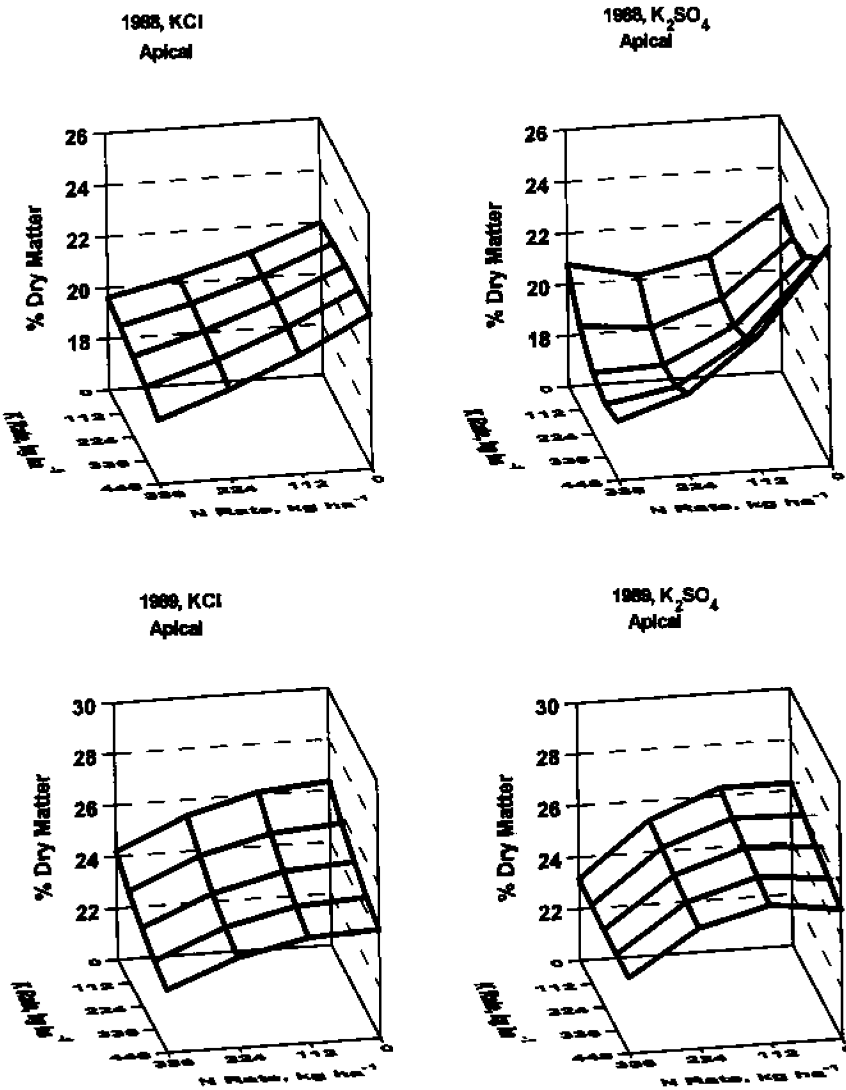

FIG. 1. Response surfaces for % dry matter in apical end in 1988 and 1989.

highest was for the 0 kg ha^{-1} N and 448 kg ha^{-1} K treatment (Data not shown). The lowest SE was for a cell that is adjacent to actual field treatments, while the highest SE was in an estimated corner cell of the 4 X 5 factorial (Table 1). Standard errors tend to be smaller in this type of design where neighboring cells reinforce the predictability of a given cell. Typically, cells on the edges and corners have less reinforcement and larger SE's.

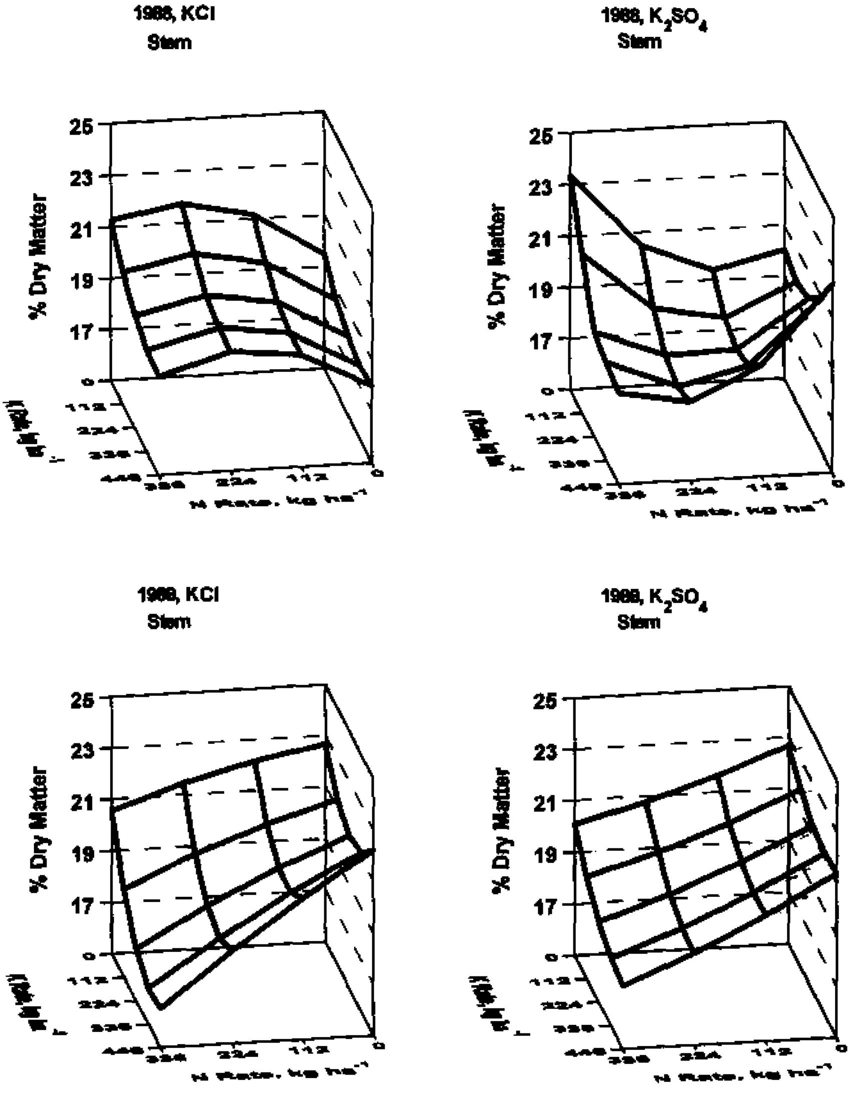

FIG. 2. Response surfaces for % dry matter in stem end in 1988 and 1989.

Overall tuber dry matter was generally higher in 1989 than in 1988 (Fig. 1 and Fig. 2). In 1988 the average dry matter of the two tuber ends were similar, while in 1989 the apical end was higher than the stem end. Nitrogen and K applications decreased the dry matter in the apical end independently of K-source (Fig. 1). The partial regression coefficient for the quadratic N effect was significant both years (Table 4). Potassium decreased dry matter linearly in 1989 but interacted with N in 1988 (Fig. 1, Table 4).

TABLE 4.—*Significance of partial coefficients for multiple linear regression equation and coefficient of multiple determination, R^2.[a] (Reducing sugar and starch expressed on a fresh [f] or dry [d] weight basis.)*

Year, Dependent Variable	Tuber end	Partial Regression coefficient											
		N	K	K_s[b]	N^2	K^2	N*K	N*K_s	K*K_s	N^2*K_s	K^2*K_s	N*K*K_s	R^2
1988													
Dry matter	Apical	****			*		*				*		0.93
	Stem		**			**	**	****		****		*	0.66
Reducing sugar$_f$	Apical	**											0.94
	Stem	****			*		*	***		***			0.96
Starch$_f$	Apical	****			*		*						0.98
	Stem		***			***	***	****		****			0.67
Starch$_d$	Apical	*											0.96
	Stem	***				***	***	**		**			0.69
1989													
Dry matter	Apical		**		***								0.98
	Stem		***			**							0.95
Reducing sugar$_f$	Apical	****			**			*		**		**	0.99
	Stem	***			**							**	0.90
Starch$_f$	Apical		**		***		**						0.97
	Stem	***	***			***	**						0.97
Starch$_d$	Apical												0.93
	Stem	****			**	**	****					**	0.99

[a]****, ***, **, * indicates significance at the 0.001, 0.01, 0.05 and 0.10 probability level, respectively. All coefficients of multiple determination, R^2, significant at the 0.001 probability level.

[b]K_s = K-source effect, KCl or K_2SO_4, entered into model as categorical variable, +1 or -1, respectively.

Dry matter effects in the stem end were more complex (Fig. 2). Both N and K reduced dry matter in 1989 but their effect depended upon K-source in 1988. The response surface was convex for KCl but concave for K_2SO_4 in 1988. Similar K-source effects were found for specific gravity in 1988 (32).

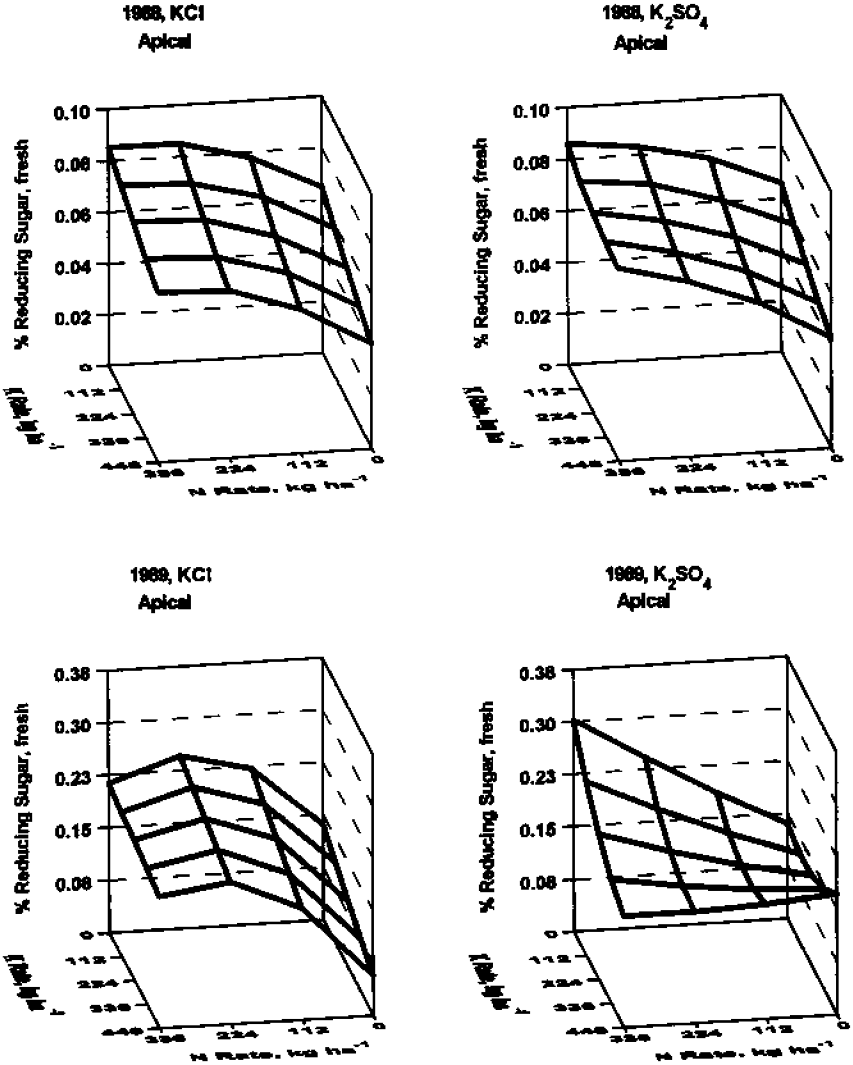

FIG. 3. Response surfaces for % reducing sugar on a fresh weight basis in apical end in 1988 and 1989.

Reducing sugar concentrations were higher in 1989 than in 1988, and higher in the stem compared with the apical end (Fig. 3 vs. Fig. 4). Nitrogen applications tended to increase or decrease reducing sugar in the apical and stem ends, respectively. The partial coefficients for quadratic N were significant, except for the apical end in 1988 (Table 4). Potassium tended to decrease reducing sugar in the apical and stem ends but specific effects were

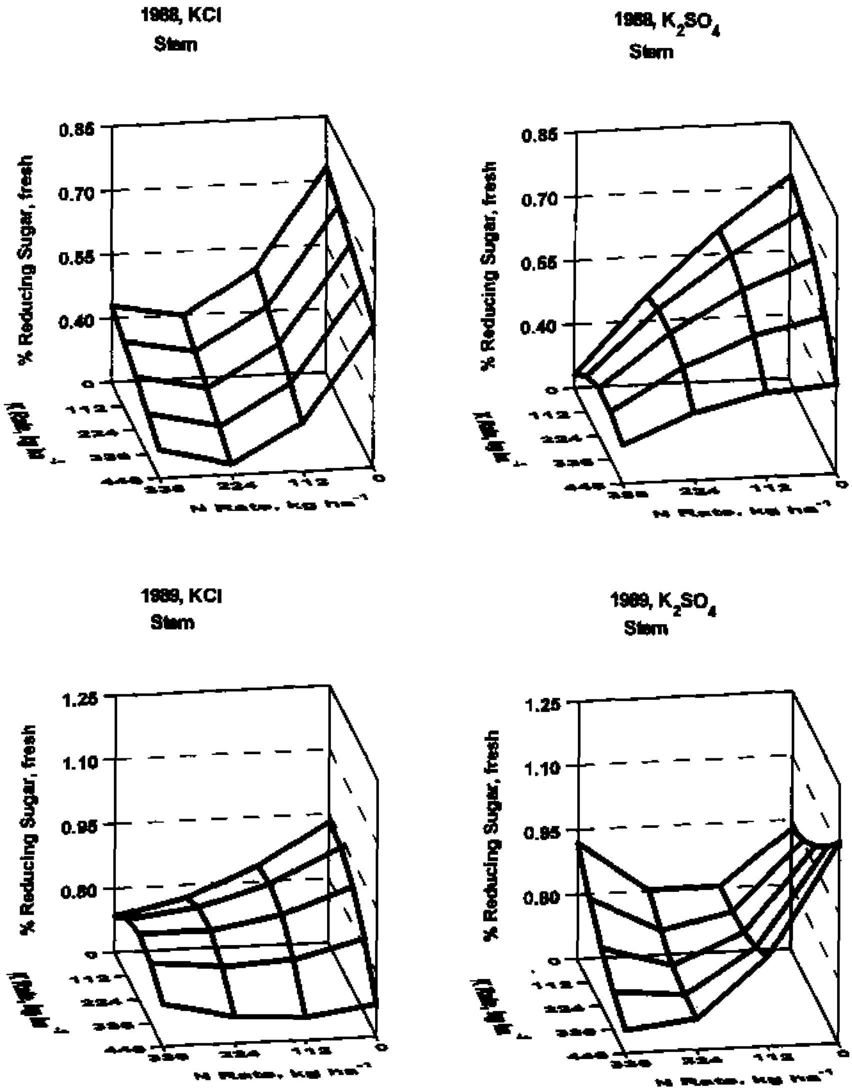

FIG. 4. Response surfaces for % reducing sugar on a fresh weight basis in stem end in 1988 and 1989.

complex and depended upon interactions with N and K-source (Figs. 3 and 4, Table 4). The lowest reducing sugar concentration in the stem end usually occurred near the highest N and K rates, while the lowest reducing sugar concentration in the apical end was with no N and near the highest K rate.

The starch (fresh weight) response surfaces looked like dry matter response surfaces (Data not shown). Similar partial coefficients were significant for both dry matter and starch (Table 4). This was expected since starch concentrations were highly correlated to dry matter and specific gravity (Table 3). Apical ends had higher starches in 1989 than in 1988, while stem ends were similar both years. Starch concentrations were generally lower in the stem compared with the apical end, particularly in 1989. Nitrogen applications tended to decrease starch concentrations both years. Linear and quadratic partial coefficients for N were significant for apical ends. Potassium tended to decrease starch, particularly at the higher N rates. Linear and quadratic partial coefficients for K were significant for stem ends both years (Table 4). The N*K interaction partial coefficient was significant both years and for both tuber ends. Potassium sources were only significant for the partial coefficients for linear and quadratic interactions with N for stem ends in 1988.

Fertilizer treatments significantly affected Cl, S, K and N concentrations in the tubers both years (ANOVA not shown). In addition, the coefficient of multiple determination, R^2, for the multiple linear regression equation for these elements was between 0.86 and 0.99, with most above 0.90

TABLE 5.—*Mean concentration (standard deviation) of nutrients in apical or stem end for each K-source in 1998 or 1989. Concentrations expressed on a dry weight basis.*

Tuber		Tuber end, 1988		Tuber end, 1989	
Nutrient	K-source	Apical	Stem	Apical	Stem
Cl	KCl	0.137 (0.057)	0.135 (0.093)	0.164 (0.075)	0.169 (0.105)
%	K_2SO_4	0.077 (0.036)	0.044 (0.025)	0.117 (0.047)	0.076 (0.046)
S	KCl	0.125 (0.007)	0.116 (0.008)	0.124 (0.003)	0.126 (0.003)
%	K_2SO_4	0.150 (0.011)	0.140 (0.015)	0.131 (0.004)	0.139 (0.007)
P	KCl	0.261 (0.011)	0.181 (0.014)	0.252 (0.023)	0.149 (0.016)
%	K_2SO_4	0.257 (0.014)	0.168 (0.018)	0.241 (0.014)	0.146 (0.008)
Zn	KCl	16.7 (0.6)	16.9 (1.7)	14.6 (0.8)	10.2 (2.4)
ppm	K_2SO_4	16.7 (0.3)	16.8 (1.7)	14.3 (1.4)	10.4 (2.3)
Cu	KCl	8.8 (0.4)	8.4 (0.4)	7.6 (0.9)	6.5 (1.2)
ppm	K_2SO_4	8.9 (0.5)	8.9 (0.9)	7.1 (1.1)	6.6 (1.0)
Mn	KCl	9.2 (0.8)	6.3 (0.5)	8.1 (0.4)	6.4 (0.8)
ppm	K_2SO_4	9.3 (0.5)	6.8 (0.8)	8.0 (0.4)	6.6 (0.9)
Fe	KCl	71.7 (17.3)	80.5 (12.1)	64.0 (8.9)	79.2 (9.7)
ppm	K_2SO_4	69.9 (6.5)	88.0 (11.9)	62.5 (6.3)	85.9 (13.1)
K	KCl	2.50 (0.13)	1.71 (0.28)	2.11 (0.14)	1.67 (0.29)
%	K_2SO_4	2.48 (0.14)	1.76 (0.29)	2.10 (0.12)	1.63 (0.23)
Ca	KCl	0.120 (0.024)	0.147 (0.013)	0.108 (0.014)	0.136 (0.022)
%	K_2SO_4	0.114 (0.015)	0.154 (0.009)	0.098 (0.008)	0.136 (0.016)
Mg	KCl	0.153 (0.012)	0.132 (0.005)	0.136 (0.006)	0.114 (0.008)
%	K_2SO_4	0.151 (0.009)	0.138 (0.009)	0.134 (0.005)	0.115 (0.006)
N	KCl	1.62 (0.17)	1.41 (0.21)	1.44 (0.24)	1.15 (0.42)
%	K_2SO_4	1.64 (0.17)	1.35 (0.23)	1.43 (0.26)	1.22 (0.43)

(Data not shown). Mean Cl concentrations were higher in the KCl than in the K_2SO_4 treatments (Table 5). Within the KCl treatment, the Cl concentration was similar in both tuber ends, however Cl was higher in the apical end in the K_2SO_4 treatments. Sulfur concentrations were slightly higher in the K_2SO_4 treatments, with no appreciable difference between tuber ends within each K-source. Nitrogen or K concentration was higher in the apical end compared with the stem end; concentrations were not affected by K-source in either tuber end (Table 5). The differences in the other nutrients appeared to depend upon their relative mobilities to the apical end, with no appreciable differences due to K-source.

Nitrogen or K concentration in each tuber end was negatively related to the starch concentration expressed on either a fresh or dry weight basis (Table 6). Chloride was positively related to starch but was only significant for the apical end. Sulfur concentration was only related to starch in the apical end. Nitrogen and chloride were also negatively related to each other in the apical and stem ends, r = -0.72 and -0.45, respectively. Chloride was related to K in only the stem end, r = 0.47. Sulfur was not significantly related to N or K, nor was N related to K in either tuber end (Data not shown).

Discussion and Conclusions

Explaining the complex relationships between nutrient concentrations and sugar-starch metabolism in the tuber is beyond the intent and scope of this paper. This discussion focuses on the nutrient relationships identified in this study that affected tuber quality. These data are for cross-sectional slices near each end of the tuber. This slice included the periderm, cortex and xylem, perimedullary and pith tissues. The periderm and cortex tissues can comprise up to 45% of the tuber solids (25) and a significant portion of the tuber's inorganic nutrient content (17). All the periderm and a portion of the cortex tissue could be lost from peeling before processing. This may reduce the significance of any relationships between inorganic

TABLE 6.—*Linear correlation coefficients*[a] *(r) between selected tuber variables (1988 and 1989).*

Tuber	Reducing sugar (fresh)		Starch (fresh)		Starch (dry)	
Nutrient	Apical	Stem	Apical	Stem	Apical	Stem
Cl	-0.07	0.23	0.46	0.07	0.49	0.28
S	-0.31	0.35	-0.36	-0.29	-0.34	-0.18
K	-0.75	-0.18	-0.86	-0.68	-0.84	-0.54
N	-0.14	-0.60	-0.79	-0.71	-0.82	-0.80

[a]r = 0.35 and 0.45 for probability levels of 0.05 and 0.01 with 30 degrees of freedom, respectively.

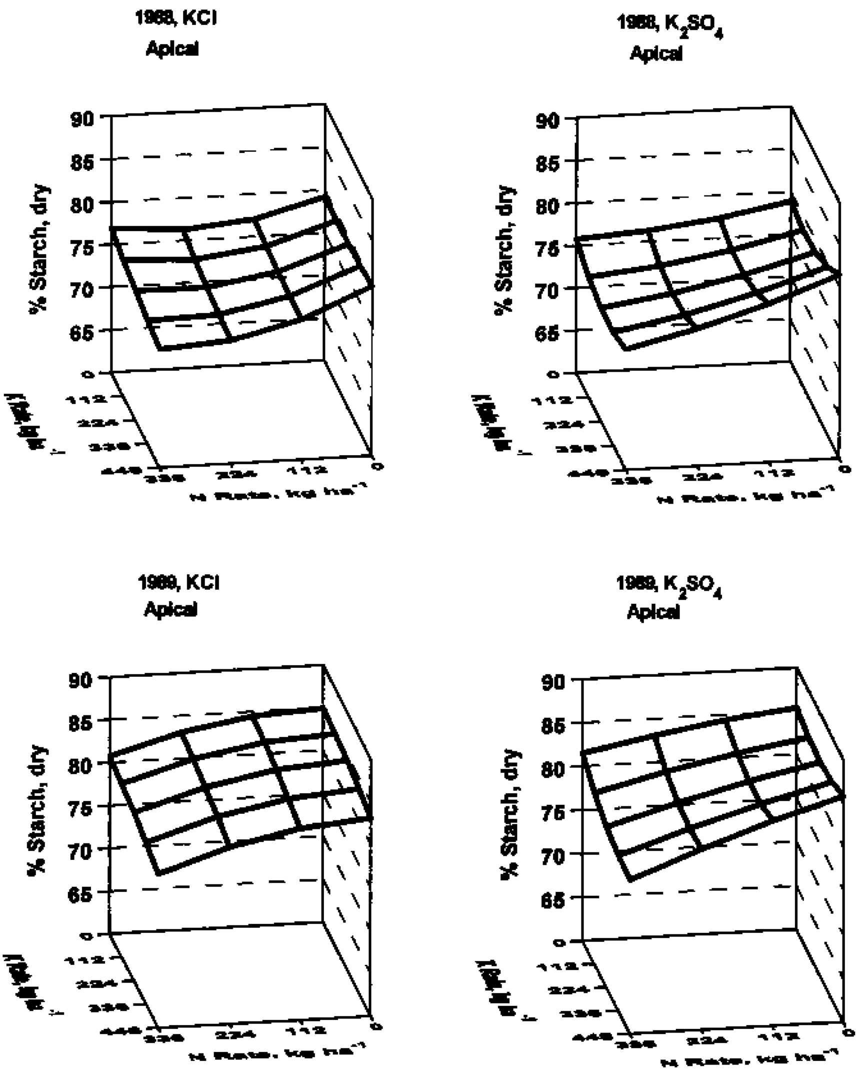

FIG. 5. Response surfaces for % starch on a dry weight basis in apical end in 1988 and 1989.

nutrient element and sugars or starch, since the nutrient concentrations in a peeled tuber would generally be lower.

Both N and K fertilizer applications reduced the dry matter in each end of the tuber, with the highest reduction in the apical end (Figs. 1 and 2). Starch was also reduced in both tuber ends, however the specific effects dependent upon year and tuber end (Table 4). The starch concentrations

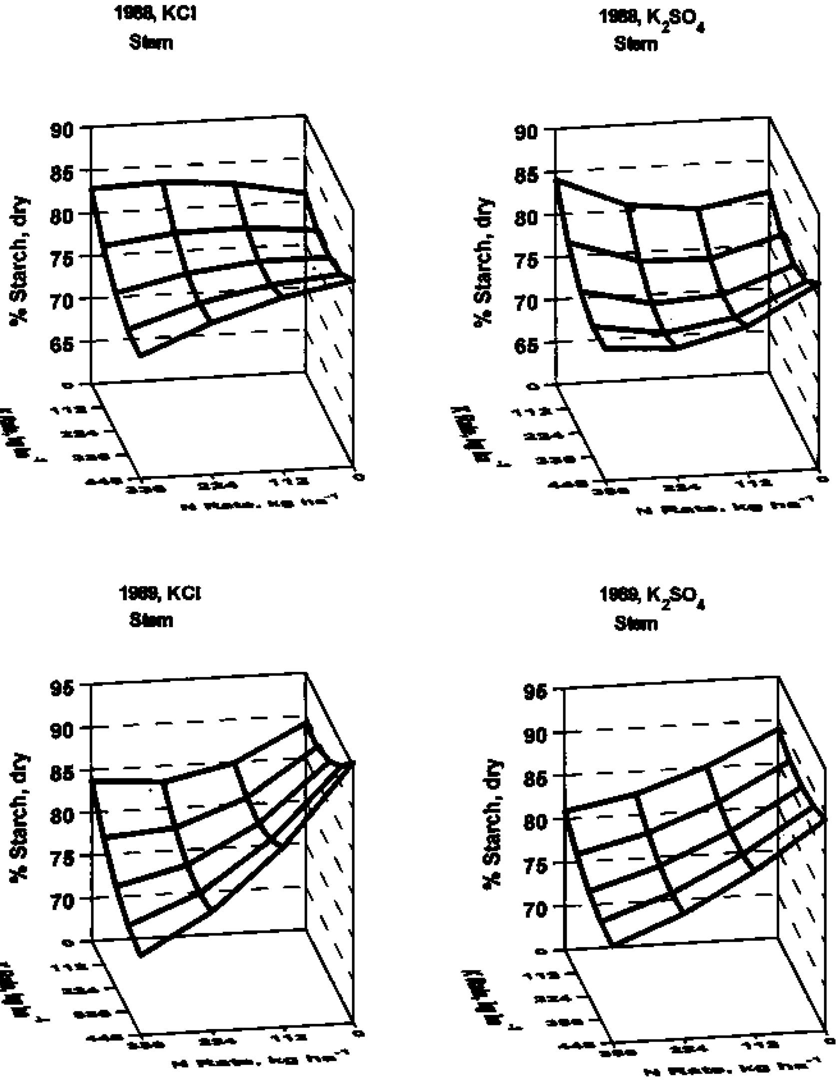

FIG. 6. Response surfaces for % starch on a dry weight basis in stem end in 1988 and 1989.

on a dry weight basis were examined to evaluate the magnitude of the water effect from K and N fertilizers (Fig. 5 and Fig. 6). Potassium had a very small effect on the starch in the apical end but decreased starch in the stem end, particularly when N was applied. Nitrogen applications reduced the starch concentrations in both tuber ends. This suggests that part of the starch (and dry matter) reduction on a fresh weight basis from K was because of increased water content to maintain cell turgor pressure against increased negative solute potential. These data are similar to those reported by Schippers (1968), who showed that most of the yield increase from N and K applications was from an increased tuber water content.

The relationships between nutrient and starch concentrations in each tuber end were evaluated with stepwise regression. Only Cl, S, K and N concentrations were used as independent variables since they were in the fertilizer materials used for treatments. Nutrients selected in the final models were N and K concentrations for both tuber ends (Table 7). Chloride was also selected for stems when starch was expressed on a dry weight basis. Regression coefficients for both N and K were negative and of a similar magnitude in all final equations; while the Cl coefficient was positive. The R^2 was highly significant for all equations. Attempts to derive one equation that included both apical and stem ends failed ($R^2 < 0.2$). Applying stepwise regression to dry matter in each tuber end gave similar equations and R^2's, except Cl was not selected for the stem end in the final model (Data not shown). Chloride was negatively correlated to N and positively to K in the stem end. In addition, Cl concentrations in the stem end increased between 3 and 10 fold when KCl was applied but only 2-fold with K_2SO_4 (Data not shown). A portion of the Cl effect could be related to its antagonistic effect on NO_3-N uptake (16). Removing it from the final equation for starch-dry weight reduced the R^2 from 0.83 to 0.79 (Table 7).

The relationships between N and K concentrations and starch in the tuber ends in our study was independent of K source. This is in contrast to other reported studies (26). A possible explanation for this discrepancy is as follows. At relatively low N availability and tuber N concentrations, increasing Cl would increase the K concentration in the tuber, reducing solids and starch. The N effect on solids or starch would be at a minimum under these conditions. This would result in a difference between K fertilizer sources. At moderate to high N availability levels, applying Cl from KCl

TABLE 7.—*Final regression equation between starch (f=fresh, d=dry) and tuber nutrients selected by stepwise regression. (All R^2 significant at 0.10% probability level with 30 degrees of freedom.)*

Tuber end	Final Regression Equation	R^2
Apical	% $Starch_f$ = 43.3 - 5.8(%N) - 7.2(%K)	0.90
Stem	% $Starch_f$ = 27.7 - 3.6(%N) - 4.2(%K)	0.80
Apical	% $Starch_d$ = 111.8 - 8.2(%N) - 8.9(%K)	0.90
Stem	% $Starch_d$ = 103.4 - 9.4(%N) - 6.4(%K)	0.79
Stem	% $Starch_d$ = 103.4 - 7.3(%N) - 9.0(%K) + 16.5(%Cl)	0.83

also increases the K concentration in the tuber but it is offset by the depression of NO_3-N uptake by Cl. The net effect would be no significant K fertilizer source effect on solids or starch. This hypothesis should be tested with a separate study.

Most tuber N is probably in the protein, amino acids and amides, although some NO_3-N accumulates in tubers as N availability increases (21). Total N in tubers is generally higher in tissues with lower total solids, *e.g.* pith and cortex (25) and apical end (in this study). The accumulation of soluble N compounds in tubers appears to contribute to the lower dry matter and starch concentrations but the mechanisms are unknown. Tuber N concentrations generally decrease with time as tubers grow and mature, and as solids increase. This could explain some of the N effect on tuber solids (dry matter, starch) in this study, particularly at the 448 kg N ha^{-1} rate since only about 224 kg N ha^{-1} was required for maximum tuber yields (32).

The K concentration in the apical end was above that required for optimum starch metabolism (*i.e.*, 1.8 % K, ref.# 10) in all treatments, but was below that concentration in the stem end when N was applied without K and at 112 kg K ha^{-1} (Data not shown). This may have contributed to a lower starch concentration, particularly when N was applied.

Reeve *et al.* (1970) concluded that "tuber tissue zones become well differentiated both histologically and physiologically relatively early in tuberization." The starch granule size distribution and composition differences are also established in relatively young tubers. Thereafter, cell division diminishes and growth is predominantly due to enlargement of cell volume in the perimedullary zone. These differences correlated with tuber quality characteristics at maturity (25). This suggests that environmental and nutritional conditions during early tuber growth may influence final tuber quality parameters, as well as yield. The influence of nutrient applications and concentrations in the plant and tuber during early development on final tuber quality parameters are unknown.

Conclusions

Nitrogen and potassium fertilizer applications significantly affected dry matter, reducing sugars, starch, and nutrient concentrations in the tuber ends. Nitrogen increased or decreased reducing sugars in the apical and stem ends, respectively. Potassium tended to decrease reducing sugars in both tuber ends. Both N and K applications reduced dry matter and starch concentrations in both tuber ends. This reduction was smaller when the starch was expressed on a dry weight basis. Both N and K concentrations in the tuber ends were negatively related to starch concentrations but the relationship was different for each tuber end. Potassium source had very little effect on tuber dry matter, reducing sugars, sucrose, or starch but indirectly affected the relationship between tuber N and K concentrations in the stem end via the Cl concentration when KCl was applied. The K fertilization effect on specific gravity depended upon the K concentration in the harvested tuber and was independent of the K source under normal fertilization practices. These data indicated that growers should avoid applying more N and K than the crop requires for production of a high quality crop.

Acknowledgments

Authors are indebted to all who reviewed this manuscript and especially to S. M. Bosma and M. A. Kay for their help and expertise in obtaining and analyzing the plant and tuber samples

Literature Cited

1. Anon. 1982. Dextrose and/or sucrose measurement in potatoes. Application note #102. 2p. Scientific Division, Yellow Springs Instrument Co., Inc., Yellow Springs, Ohio 45387.
2. Anon. 1983. United States Standards for grades of potatoes for processing. 48 FR 10801. Revised, effective April 14, 1983.
3. Anon. 1984. Starch analysis: specification sheet. 2p. Scientific Division, Yellow Springs Instrument Co., Inc., Yellow Springs, Ohio 45387.
4. Beringer, H., H.E. Haeder and M. Lindhauer. 1983. Water relationships and incorporation of ^{14}C assimilates in tubers of potato plants differing in potassium nutrition. Plant Physiol 73:956-960.
5. Beringer, H., K. Koch and M.G. Lindhauer. 1990. Source:sink relationships in potato *(Solanum tuberosum)* as influenced by potassium chloride or potassium sulphate nutrition. Plant Soil 124:287-290.
6. Beukema, H.P. and D.E. van der Zaag. 1990. Introduction to potato production. 208 p. Pudoc Wageningen, Netherlands.
7. Budke, C.C. 1984. Determination of total available glucose in corn base materials. J Agric Food Chem 32:34-37.
8. Chapman, K.S.R., L.A. Sparrow, P.R. Hardman, D.N. Wright and J.R.A. Thorp. 1992. Potassium nutrition of Kennebec and Russet Burbank potatoes in Tasmania: Effect of soil and fertilizer potassium on yield, petiole and tuber potassium concentrations, and tuber quality. Aust J Expt Agric 32:521-527.
9. Flowers, T.J. 1988. Chloride as a nutrient and as an osmoticum. Adv Plant Nutrition 3:55-78.
10. Forster, H. and H. Beringer. 1983. Starch content of potato tubers in relation to K nutrition and tuber growth. Z Pflanzenernaehr Bodenk 146:572-582.
11. Haeder, H.E. 1976. The influence of chloride nutrition in comparison with sulphate nutrition on assimilation and translocation of assimilates in potato plants. Landw Forsch 32:122-131.
12. Haeder, H.E., K. Mengel and H. Forster. 1973. The effect of potassium on translocation of photosynthates and yield pattern of potato plants. J Sci Fd Agric 24:1479-1487.
13. Harrap, F.E.G. 1960. Some aspects of the potash nutrition of the potato. J Sci Fd Agric 11:295- 298.
14. Herlihy, M. and P.J. Carroll. 1969. Effects of N, P, and K and their interactions on yield, tuber blight and quality of potatoes. J Sci Fd Agric 20:513-517.

15. Iritani, W.M. and L. Weller. 1978. Influence of low fertility and vine killing on sugar development in apical and stem portions of Russet Burbank potatoes. Am Potato J 55:239-246.

16. James, D.W., R.L. Hurst, D.T. Westermann and T.A. Tindall. 1994. Nitrogen and potassium fertilization of potatoes: Evaluating nutrient element interactions in petioles with response surfaces. (Accepted by Am Potato J, Nov. 1993).

17. Johnson, F.B., I. Hoffman and A. Petrasovits. 1968. Distribution of mineral constituents and dry matter in the potato tuber. Am Potato J 45:287-292.

18. Kunkel, R. and N. Holstad. 1972. Potato chip color, specific gravity and fertilization of potatoes with N-P-K. Am Potato J 49:43-62.

19. Lindhauer, M.G. and M.A.R. De Fekete. 1990. Starch synthesis in potato *(Solanum tuberosum)* tubers: Activity of selected enzymes in dependence of potassium content in storage tissue. Plant Soil 124:291-295.

20. Mazza, G. 1983. A comparison of methods of analysis for sugars in potato tubers. Can Inst Fd Sci Tech J 16:234-236.

21. McDole, R.E. and G.M. McMaster. 1978. Effects of moisture stress and nitrogen fertilization on tuber nitrate-nitrogen content. Am Potato J 55:611-619.

22. Mica, B. 1988. Relations between the content of starch and the content of potassium in potato tubers. Starch/Starke 40:288-290.

23. Neter, J., W. Wasserman and M.H. Kutner. 1989. Applied linear regression models. Richard D. Irwin, Inc., Homewood, Ill, 60430. 667 p.

24. Nitsos, R.E. and H.J. Evans. 1969. Effects of univalent cations on the activity of particulate starch synthetase. Plant Physiol 44:1260-1266.

25. Reeve, R.M., E. Hautala and M.L. Weaver. 1970. Anatomy and compositional variations within potatoes. III. Gross compositional gradients. Am Potato J 47:148-162.

26. Roberts, S. and R.E. McDole. 1985. Potassium nutrition of potatoes. p. 799-818. *In:* R. D. Munson (ed.). Potassium in Agriculture. Proc Int Sym PPI, ASA, CSSA, SSSA, July 7-10, 1985. Madison, WI.

27. Schippers, P.A. 1968. The influence of rates of nitrogen and potassium application on the yield and specific gravity of four potato varieties. Eur Potato J 11:23-33.

28. Schippers, P.A. 1976. The relationship between specific gravity and percentage dry matter in potato tubers. Am Potato J 53:111-123.

29. Sharma, U.C. and B.R. Arora. 1988. Effect of applied nutrients on the starch, proteins and sugars in potatoes. Food Chem 30:313-317.

30. Shekhar, V.C. and W.M. Iritani. 1978. Starch to sugar interconversion in *Solanum Tuberosum* L. I. Influence of inorganic ions. Am Potato J 55:345-350.

31. Terman, G.L., P.N. Carpenter and C.E. Cunningham. 1953. Relation of soil and fertilizer to dry matter content and yield of potatoes. Soil Sci 75:449-458.

32. Westermann, D.T., T.A. Tindall, D.W. James and R.L. Hurst. 1994. Nitrogen and potassium fertilization of potatoes: Yield and specific gravity. Am Potato J 71:417-431.