

Reprint from: Proc. 22nd Colloquium Int. Potash Institute, Bern (1990)

Dynamics of Soil Potassium in Multicationic Systems

*Sala Feigenbaum, A. Bar-Tal and D. L. Sparks**

Dynamics of Soil Potassium in Multicationic Systems

*Sala Feigenbaum, A. Bar-Tal and D.L. Sparks**

Summary

The increasing use of brackish water for irrigation calls for more information on the effect of water salinity and ion composition on potassium reactions in soil and on the availability of K to plants. The objectives of this work were to: (i) study plant response to K as affected by salinity; (ii) study K dynamics in soil as affected by irrigation with saline-sodic water; and (iii) test the validity of exchange selectivity coefficients obtained in binary systems for prediction of ternary exchange of K in a multicationic system. The reactions and fate of native and fertilizer K under saline conditions were studied in two soils in a greenhouse pot experiment with corn (*Zea mays* (L.) cv. «Jubilee»). Potassium adsorption by the soils from multicationic solutions was studied using batch and miscible-displacement methods in the laboratory. Salinity level in the irrigation water had a significant effect on yield decrease in both soils and there was a significant yield response to K application in the Nordiya soil. In both soils K fertilization increased K concentration and reduced the ratio Na:K in plant tissue. Potassium application moderated exchangeable K depletion in both soils. Potassium was preferred over the divalent cations Ca and Mg in both soils, regardless of the experimental method and Na concentration. A simple mathematical solution of the Gapon binary equations for K-(Ca+Mg) and Na-(Ca+Mg), in combination with the assumption of a constant CEC, was used to predict the amount of exchangeable K as a function of solution composition. The ability to predict the exchange of K with Ca+Mg and Na in a miscible displacement system using information obtained in binary systems was evaluated.

1. Introduction

Release of interlayer K from mica-like minerals in semiarid and arid regions is a source of plant available K, but the major source of K for plant nutrition in most agricultural soils is exchangeable K (*McLean and Watson [1985]*). Exchangeable K is most commonly used as an index for estimating available K (*Carson and Dixon [1972]*). However, this parameter does not always adequately predict response to applied K since non-exchangeable K forms can

* Dr. *Sala Feigenbaum* and *A. Bar-Tal*, Institute of Soils and Water, Agricultural Research Organization, The Volcani Center, Bet Dagan 50250, Israel; Dr. *D.L. Sparks*, Dept. of Plant and Soil Science, University of Delaware, 147 Townsend Hall, Newark, DE 19717-1303, USA

play an important role in supplying K to plants over a period of time (*Feigenbaum and Hagin [1967]; Sadusky et al. [1987]*). Fertilizer recommendations under non-saline conditions are based on crop requirement and K availability indexes (*Mengel and Kirkby [1980]*). Available K is expressed basically as a ratio between K concentration and (Ca + Mg) concentration in the soil solution which is in equilibrium with the solid phase of the soil (*Beckett [1971]; Woodruff [1955]*). This ratio is an intensity index, and exchangeable K a capacity index (*McLean and Watson [1985]*).

Potassium, one of the major plant nutrients, may behave differently under saline and non-saline conditions, from both plant and soil aspects. Sewage effluents and brackish waters contain considerable quantities of cations such as Na^+ , K^+ , Ca^{+2} and Mg^{+2} . These cations undergo simultaneous exchange reactions with each other on the soil surface. For example, the possible reactions involving K-Ca-Mg, K-Na-Ca and K-Na-Mg in soils, and the study of their effect on K distribution between the solution and the solid phases are extremely important for plant nutrition. Irrigation with brackish water, in which the concentrations of Ca, Mg and Na are higher than in good quality water might cause an increase in downward movement of K beyond the root zone. With increasing concentrations of competing cations, larger fractions of K from the soil or from fertilizer sources are found in the solution phase (*Feigenbaum et al. [1988]*). Thus K may be more available to plant roots, but is also easily leached from the root zone, especially where excess leaching is required to ameliorate soil salinity (*Feigenbaum [1986]*).

Salinity and low K fertility are important growth limiting factors; decreasing or eliminating one factor may affect the crop's response to the other (*Feigin [1985]*). Research on the interaction between salinity and fertility as it affects crop response has been reviewed by *Feigin [1985]* and *Kafkafi [1985]*, but most of the studies have been concerned with salt-plant nutrition relationships for applied N and P fertilizers and only a few have involved K.

Exchange reactions involving K with cations such as Ca, Mg and Na in clay minerals and soils, have been investigated intensively and reviewed by *Bolt [1979]* and *Sparks [1987]*. Our theoretical understanding of the relationship between ternary and binary exchange systems in clays and soils has improved during the last decade. Chemical and geochemical models were adapted to soils for predicting cation exchange in a ternary system using binary exchange data (*Elprince et al. [1980]*). *Chu and Sposito [1981]*, using data obtained from careful experiments with pure clay minerals, found that the effect of the ternary systems on the binary exchange coefficient was no greater than the experimental error. Unfortunately, reports that have appeared in the soil chemistry literature on exchange phenomena involving binary and particular ternary systems, do not involve K (*Chu and Sposito [1981]; Elprince et al. [1980]*). The objectives of the current research were to: (i) study plant response to K as affected by salinity; (ii) study K dynamics in soil as affected by irrigation with saline-sodic water; and (iii) test the validity of exchange selectivity coefficients obtained in binary systems for prediction of ternary exchange of K in multicationic system.

2. Materials and Methods

Two soils, representing high and low available K, were chosen for the study of the interactive effect of salinity and fertility on plant growth and the dynamics of K reactions in soil. The soils were collected from control plots of fields where irrigation experiments with brackish water were being conducted: one from the south of Israel – at Gilat, and one from the Coastal Plain – at Nordiya. The basic chemical and physical properties of the soils were determined using standard methods and their properties are given in Table 1. This study included a corn pot experiment in a greenhouse, and a laboratory study of K exchange reactions in a multicationic system.

Table 1. Selected chemical and physical properties of the studied soils

Soil	Soil Subgroup	CaCO ₃	Organic matter	Particle size			Texture	pH	CEC	Exch. K
				Sand	Silt	Clay				
			g kg ⁻¹						cmolkg ⁻¹	
Gilat	Calcic Haploxeralf	203.0	9	436	368	196	1	7.8	11.0	0.80
Nordiya	Typic Rhodoxeralf	1.4	14	854	48	98	s	7.5	6.2	0.50

2.1 Corn pot experiment

Sweet corn (*Zea mays* (L.) cf. «Jubilee») was grown in pots containing 3.0 kg of air dry soil. The experiment included nine treatments in six replications in a factorial design. Potassium application rates per pot were: 0, 15 and 30 mmol K in the Gilat soil and 7.5, 15 and 30 mmol K in the Nordiya soil. The salinity levels S₁, S₂ and S₃ of the irrigation water were 4, 20 and 40 mmol charge L⁻¹, respectively, with SAR values of 10 for S₂ and S₃, using a salt mixture of NaCl, CaCl₂ and Ca(NO₃)₂ in both soils. The plants were irrigated daily to bring to volumetric water fraction at pot capacity, plus 10–20% leaching (for more details see Bar-Tal et al. [1990]). Irrigation and drainage volumes were determined throughout the experiment period. After the last harvest, 58 days after seeding, the soil in each pot was divided into four horizontal layers and exchangeable K and Na were extracted from the soils using 1M ammonium acetate. The leachate and saturated pastes of the soils were analyzed for EC, Cl, K, Na, Ca and Mg.

2.2 Laboratory experiment

Exchange isotherms for binary and ternary systems of K, Na, Ca and Mg were performed with each studied soil at room temperature, 286±2.0 K, to obtain a complete description of the exchange reactions. Binary exchange

reactions were conducted using a batch technique. Soil samples were equilibrated with two sets of solutions with a constant ClO_4 concentration of $20 \pm 0.5 \text{ mol m}^{-3}$: the first with a K-Mg salt mixture and the second with Na-Mg. The initial Mg-equivalent fraction in the solution of the two sets varied from 0 to 1, using two replicates. Soil samples were equilibrated with the different salt mixture solutions, at a soil:solution ratio of 1:5.

Ternary exchange reactions were conducted using a miscible-displacement technique (*Jardine and Sparks [1984]*). The soils were equilibrated with solutions with a varied K/Na/Ca/Mg ratio in a constant Cl background concentration of $20 \pm 0.5 \text{ mol m}^{-3}$. Exchangeable cations were extracted with 0.5 M LiCl solution in batch and miscible-displacement methods (for more details see *Feigenbaum et al. [1990]*). Potassium and Na concentrations in the equilibrium and displaced solutions from the binary and ternary systems were determined by flame photometry. Calcium and Mg in the equilibrium solutions were determined by atomic absorption spectrometry.

Calcareous soils pose difficulties in the determination of adsorbed Ca and Mg. Consequently, the adsorbed Ca plus Mg in each treatment was calculated from the difference between the total CEC (Table 1) and the displaced Na and K, assuming constant CEC. This assumption is based on published data showing constant CEC of montmorillonite and montmorillonitic soils (*El-prince et al. [1980]*; *Jensen [1973]*). From the above batch and miscible displacement techniques, K-(Ca + Mg) isotherms were drawn to present the adsorbed cation ratio as a function of soluble cation and the Gapon model was used to calculate selectivity coefficients, k_G .

3. Results

3.1 Corn pot experiment

Fresh and dry weights of corn, for a given K treatment, decreased significantly with increasing salinity level in both soils (Table 2). In the Nordiya soil there was a significant positive yield response to K application 46 days after seeding. There was a significant interaction in yield response between K application and salinity level of the irrigation water at the last harvest (Table 2). Hence, at this harvest, the effect of K was analyzed separately for each salinity level and significant yield increase was obtained in S_2 water, while in S_1 there was yield increase from K_1 to K_2 and an unexplained decrease from K_2 to K_3 ; there was no significant effect of K application on yield using S_3 .

Potassium concentration in the plant tissue was enhanced by K increasing the K application rate and the salinity level of the irrigation water. Sodium concentration of the plant tops was not affected by K application in the Gilat soil, while in the Nordiya soil there was an interaction between K application and salinity effects on the tissue Na content; K application significantly reduced the plant tissue concentration only in the high salinity irrigation. Potassium application reduced by a factor of 1.5–3.0 the Na:K plant molar

concentration ratio, which has been considered an important factor in the effect of sodic saline water on plant growth (*Läuchli and Stelter [1982]; Helal and Mengel [1979]*).

Table 2. Corn yield and plant K and Na concentration as affected by salinity and K application

Treatment	Fresh weight (g/plant)		Nutrient content at last harvest (mol/kg)		
	46 day	58 day	K	Na	Na/K
	Gilat				
K ₁ S ₁	91.27	126.80	0.37	0.02	0.04
K ₂ S ₁	91.43	138.90	0.53	0.01	0.02
K ₃ S ₁	108.00	135.49	0.60	0.01	0.02
K ₁ S ₂	66.07	89.49	0.49	0.28	0.57
K ₂ S ₂	62.08	99.32	0.63	0.23	0.36
K ₃ S ₂	61.48	92.80	0.74	0.29	0.39
K ₁ S ₃	50.37	63.69	0.52	0.47	0.91
K ₂ S ₃	50.28	67.43	0.69	0.40	0.58
K ₃ S ₃	48.83	81.84	0.79	0.47	0.60
Source df			Probability > F		
Model 10	0.000	0.000	0.000	0.000	0.000
Block 2	0.442	0.123	0.150	0.273	0.160
S 2	0.000	0.000	0.000	0.000	0.000
K 2	0.487	0.184	0.000	0.185	0.001
S · K 4	0.200	0.615	0.925	0.821	0.160
	Nordiya				
K ₁ S ₁	97.27	174.39	0.12	0.01	0.08
K ₂ S ₁	101.50	204.68	0.18	0.01	0.06
K ₃ S ₁	122.97	173.27	0.31	0.01	0.03
K ₁ S ₂	88.35	129.11	0.17	0.37	2.21
K ₂ S ₂	95.90	139.10	0.24	0.47	1.94
K ₃ S ₂	96.32	159.26	0.43	0.43	1.01
K ₁ S ₃	69.45	110.75	0.19	0.62	3.30
K ₂ S ₃	77.38	104.84	0.34	0.58	1.73
K ₃ S ₃	76.33	121.54	0.50	0.48	0.95
Source df			Probability > F		
Model 10	0.000	0.000	0.000	0.000	0.000
Block 2	0.198	0.785	0.164	0.440	0.760
S 2	0.000	0.000	0.000	0.000	0.000
K 2	0.003	0.035	0.000	0.196	0.000
S · K 4	0.087	0.001	0.000	0.029	0.000

Soil analyses after the harvest show that K_{solub} , K_{exch} and PAR, which have been widely used as availability parameters, were increased significantly by K application, indicating that the K application treatment was indeed effective (Table 3). After the last harvest, the exchangeable K levels in the Nordiya and Gilat soils under low and medium K application dropped considerably below the initial exchangeable K values found in the soils. Even though there was no corn yield response to K application in the Gilat soil, the highest K application eliminated exchangeable K depletion (Table 3). Large differences in exchangeable K between the Nordiya and Gilat soils were found in identical treatments. The highest capacity parameter for available K (exchangeable K) in the Nordiya soil was $0.28 \text{ cmol kg}^{-1}$ which was lower than the lowest value in the Gilat soil, $0.32 \text{ cmol K kg}^{-1}$. In both soils, soluble and exchangeable Na were a function of the salinity of the irrigation water, but were unaffected by K applications.

Table 3. Concentration of soluble and exchangeable ions in Gilat and Nordiya soils as affected by K and salinity treatments

Treatment	Cl	K	Soluble (meq L^{-1})				PAR	Exchangeable (cmol kg^{-1})			
			Na	Ca	Mg	PAR		SAR	EXK	EXNa	EPP
Gilat											
K_1S_1	1.8*	0.05	1.66	4.52	1.03	0.032	1.4	0.32	1.32	2.91	
K_2S_1	2.0	0.09	1.56	4.32	1.19	0.056	1.3	0.39	1.45	3.55	
K_3S_1	2.4	0.19	1.16	3.71	1.27	0.122	1.0	0.55	1.12	5.00	
K_1S_2	62.9	0.11	47.94	9.39	2.87	0.043	27.6	0.32	2.67	2.71	
K_2S_2	50.5	0.18	40.73	5.76	1.70	0.095	30.3	0.45	3.33	4.09	
K_3S_2	57.5	0.54	45.11	7.94	2.50	0.234	28.1	0.71	2.86	6.45	
K_1S_3	101.8	0.18	60.51	19.93	5.19	0.050	24.5	0.37	3.18	3.36	
K_2S_3	102.1	0.43	62.57	21.09	4.75	0.119	25.5	0.57	3.14	5.18	
K_3S_3	103.3	0.95	60.94	18.90	4.68	0.277	26.4	0.78	3.36	7.09	
Nordiya											
K_1S_1	1.4	0.08	1.47	6.59	0.28	0.042	0.8	0.18	1.26	2.88	
K_2S_1	2.2	0.10	1.73	8.09	0.34	0.047	0.8	0.19	1.45	3.04	
K_3S_1	2.2	0.11	1.68	7.00	0.34	0.055	0.9	0.20	1.31	3.20	
K_1S_2	25.8	0.06	27.26	4.15	0.24	0.037	18.7	0.14	2.51	2.24	
K_2S_2	22.4	0.07	24.15	4.60	0.26	0.045	15.8	0.17	2.37	2.72	
K_3S_2	24.9	0.09	27.38	4.59	0.24	0.058	18.1	0.20	2.53	3.20	
K_1S_3	53.3	0.08	41.47	15.93	0.34	0.026	14.9	0.15	2.42	2.40	
K_2S_3	49.7	0.11	39.17	15.15	0.40	0.039	14.3	0.16	2.39	2.56	
K_3S_3	52.8	0.28	42.83	17.37	0.45	0.092	14.7	0.28	2.44	4.48	

* Represents average concentrations for the four soil layers

A linear relation between the exchangeable potassium percentage ($\text{EPP} = 100 q_K / \text{CEC}$) and the soluble cation ratio ($\text{PAR} = C_K / (C_{Ca} + C_{Mg})^{1/2}$) was obtained in both soils (Figure 1). In the current study this relationship was found

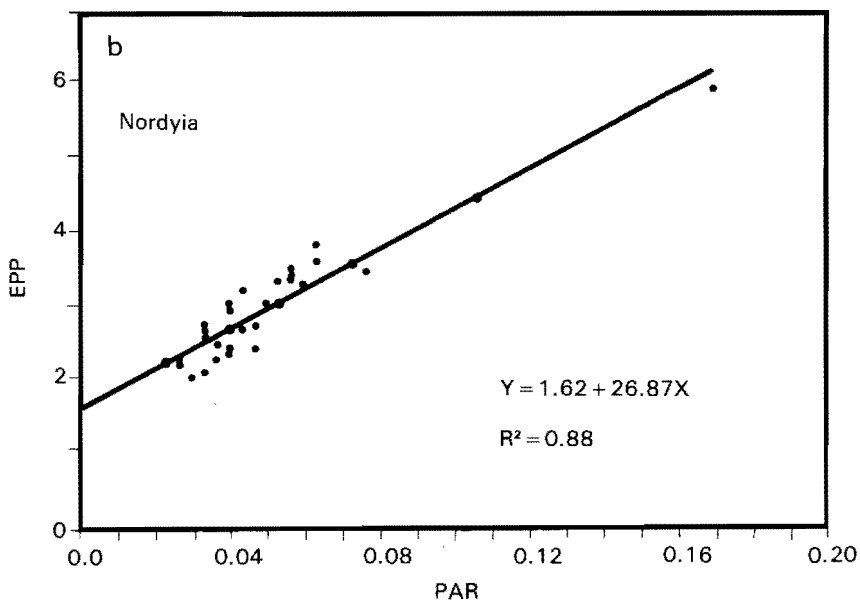
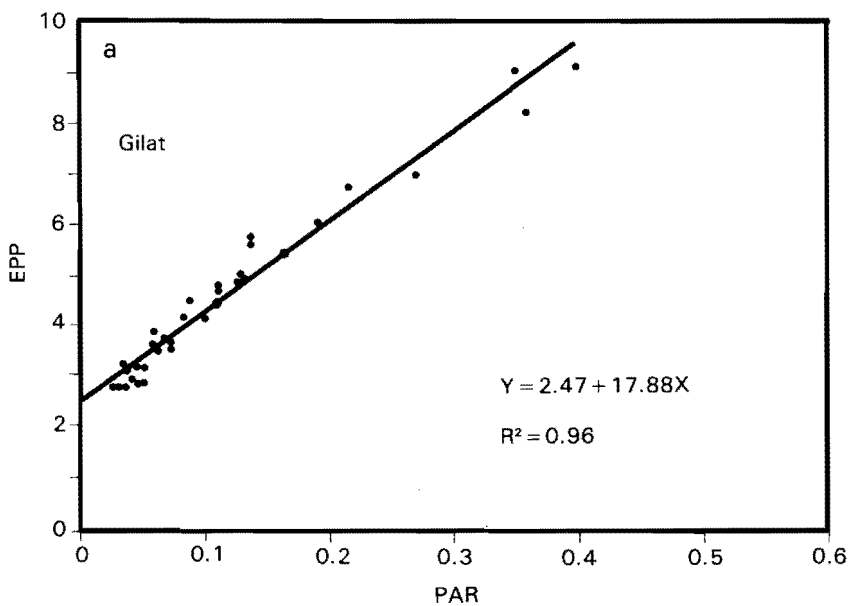


Figure 1. Exchangeable potassium percentage (EPP) as a function of the potassium adsorption ratio (PAR) in the solution of the soil pastes obtained in the pot experiment under three salinity levels.

to be independent of soil salinity and for a wide range of Na concentrations: from 2 to 60 mmol L⁻¹ for the Gilat soil, and from 2 to 43 mmol L⁻¹ for the Nordiya soil (Table 3). The SAR values were similar over a wide range and neither one directly affected the relation between adsorbed and soluble K fractions. All the results can be described by one linear regression line for each soil (Figure 1). The slopes and intercepts were related to the soil type. In order to understand the effect of Na on K exchange with (Ca + Mg) in these soils, binary and ternary exchange experiments were conducted.

3.2 Binary and ternary exchange experiments

Potassium exchange with the divalent cations, Ca and Mg, was analyzed, treating Ca and Mg as identical cations, following the approach of the *US Salinity Laboratory Staff [1954]*. This approach was justified by the non-preference of Ca over Mg for the Nordiya (*Seyfried et al. [1989]*) and Gilat soils (*Feigenbaum et al. [1990]*). To determine which cation is preferred over the other in mono-divalent exchange systems, the renormalized K equivalent fractions in solution, E_K' , and on the solid phase, \hat{E}_K' , were calculated according to *Theilier and Sposito [1988]*, excluding Na concentration in both phases:

$$E_K' = \frac{C_K}{C_K + 2(C_{Ca} + C_{Mg})} \quad (1)$$

$$\hat{E}_K' = \frac{q_K}{q_K + 2(q_{Ca} + q_{Mg})} \quad (2)$$

where C is the concentration in the soluble phase (mol L⁻¹), and q is the quantity of adsorbed cations (mol kg⁻¹). The isotherms of \hat{E}_K' vs E_K' for the Nordiya and Gilat soils are presented with calculated lines (after *Jensen [1973]*) for nonpreference and ideal solution conditions for the liquid and solid phases (Figures 2a, 2b). The experimentally observed points for the two soils lie well above the theoretical curve, indicating a preference for K over (Ca + Mg). Similar results were found for clay minerals and for soils (*Jensen [1973]*; *Schwertmann [1962]*). To examine whether sodium concentration affected K exchange with (Ca + Mg), isotherms of \hat{E}_K' vs E_K' , obtained from the ternary system (Table 4) were compared with the binary isotherms. It can be seen that the presence of Na in the ternary system did not alter the curve of \hat{E}_K' vs E_K' , in either the Nordiya or the Gilat soil, respectively (Figures 2a, b).

The selectivity coefficients (k_G) for the exchange reaction in the binary and ternary systems were determined using the following modified Gapon model (*Sposito and Mattigod [1987]*), in which ion activity ratio and mol L⁻¹ units are used, rather than concentration and mmol L⁻¹ units, as used by *Gapon [1933]*.

$$\text{EPR} = k_{\text{GK}} \text{PAR}_i \quad (3)$$

where

$$\text{PAR}_i = \frac{a_{\text{K}}}{f(C_{\text{Ca}} + C_{\text{Mg}})^{1/2}} \text{ and } \text{EPR} = \frac{q_{\text{K}}}{(2q_{\text{Ca}} + 2q_{\text{Mg}})}$$

and

$$\text{ESR} = k_{\text{GNa}} \text{SAR}_i \quad (4)$$

where

$$\text{SAR}_i = \frac{a_{\text{Na}}}{f(C_{\text{Ca}} + C_{\text{Mg}})^{1/2}} \text{ and } \text{ESR} = \frac{q_{\text{Na}}}{(2q_{\text{Ca}} + 2q_{\text{Mg}})}$$

Table 4. Miscible displacement exchange data for K with Na, Ca and Mg in 20 mol m⁻³ Cl background

C _K	C _{Na}	C _(Ca + Mg)	PAR _i	SAR _i	q _K	q _{Na}	q _{Ca} + q _{Mg} *	k _G
mol m ⁻³			(mol/L) ^{0.5}		cmol kg ⁻¹			(mol/L) ^{0.5}
Gilat								
2.2	10.3	4.12	0.034	0.161	1.28	0.52	3.90	4.9
2.2	10.1	4.00	0.034	0.159	1.64	0.35	3.81	6.3
4.3	5.0	5.72	0.057	0.066	1.97	0.35	3.64	4.7
4.3	9.8	3.19	0.077	0.173	2.30	0.35	3.47	4.3
4.2	12.1	2.13	0.091	0.259	2.65	0.38	3.28	4.4
6.1	10.2	2.08	0.134	0.223	3.31	0.32	2.98	4.1
5.4	12.6	1.18	0.157	0.366	3.32	0.61	2.83	3.7
7.2	9.2	2.08	0.158	0.202	3.32	0.52	2.88	3.6
7.7	8.7	2.13	0.165	0.187	3.02	0.26	3.16	2.9
8.6	7.9	2.08	0.187	0.174	3.92	0.13	2.71	3.9
9.6	7.1	2.08	0.210	0.154	3.78	0.22	2.81	3.2
10.5	6.0	2.13	0.226	0.129	4.38	0.21	2.51	3.9
14.7	5.4	1.38	0.434	0.160	5.00	0.70	1.95	2.9
Nordiya								
2.2	10.1	4.21	0.033	0.156	0.69	0.22	2.10	4.7
2.2	10.3	3.95	0.035	0.164	0.64	0.22	2.22	4.2
4.3	4.9	5.67	0.058	0.066	0.95	0.17	2.09	4.0
4.3	9.8	2.81	0.082	0.185	1.12	0.22	1.98	3.5
4.2	12.0	2.13	0.090	0.259	1.35	0.23	1.86	4.0
6.1	9.8	2.08	0.134	0.214	1.53	0.18	1.79	3.2
7.1	3.9	4.55	0.147	0.058	1.76	0.01	1.77	3.4
7.3	9.2	2.15	0.157	0.199	1.41	0.18	1.86	2.4
7.7	8.7	2.06	0.169	0.191	1.66	0.43	1.61	3.1
5.4	12.6	0.94	0.177	0.410	1.60	0.27	1.71	2.6
8.6	7.9	2.08	0.187	0.174	1.81	0.13	1.68	2.9
9.8	7.0	1.94	0.223	0.158	2.24	0.27	1.39	3.6
10.5	6.0	2.13	0.227	0.129	2.12	0.11	1.53	3.0
14.3	5.0	0.97	0.459	0.160	2.65	0.16	1.24	2.3

* Calculated as the difference between total CEC and q_K+q_{Na}.

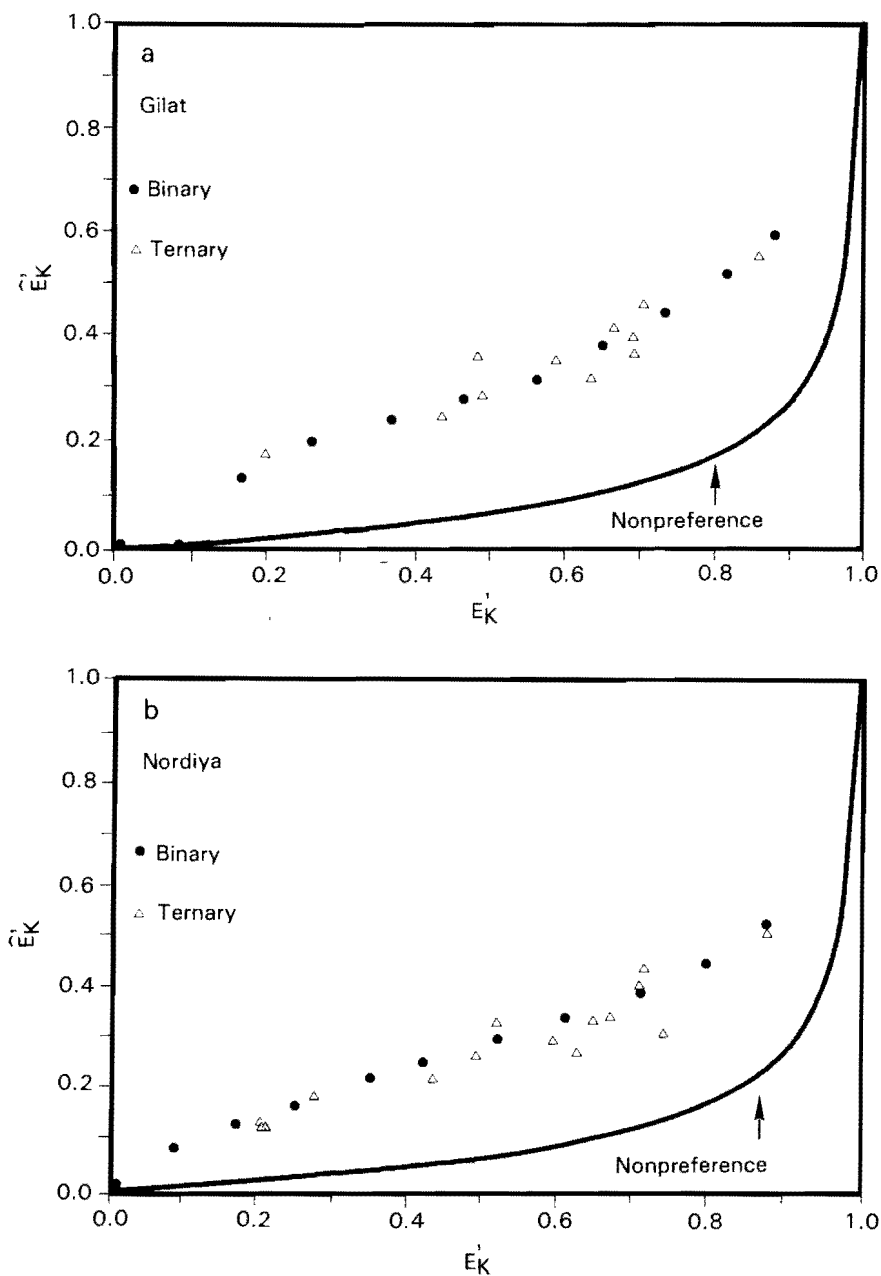


Figure 2. Renormalized isotherm for K exchange with (Ca+Mg) in binary and ternary systems.

where a and f are ion activity (mol L^{-1}) and activity coefficient in the solution, respectively. The activities of the cations in the solutions were calculated using the Davies equation (*Sposito [1981]*). The observed exchangeable potassium ratio (EPR) as a function of solution K ratio (PAR_i) of the two soils with the regression lines is presented in Figures 3a, b. The k_{GK} value in the Nordiya and Gilat soils was 2.4 ± 0.05 and 2.9 ± 0.04 (mol L^{-1})^{0.5} with r^2 values of 0.989 and 0.996, respectively. Sodium exchange with (Ca+Mg) in the Nordiya and Gilat soils is presented in Figures 4a, b. The values of k_{GNa} for the Nordiya and Gilat soils were 0.28 ± 0.01 and 0.42 ± 0.02 (mol L^{-1})^{0.5}, with r^2 values of 0.98 and 0.99, respectively. The values of k_{G} for K-(Ca+Mg) and Na-(Ca+Mg) exchange in both soils are of the same magnitude as published values for montmorillonite and montmorillonitic soils (*Bolt [1979]; U.S. Salinity Lab Staff [1954]*). Despite the high correlation of EPR with PAR_i in both soils, there are large deviations of the observed data from the model for low EPR values. To improve the prediction of EPR as a function of activity ionic ratio in the solutions (PAR_i), empirical functions relating k_{GK} values to corresponding EPR were determined using the SAS STEPWISE PROCEDURE (*SAS [1985]*) and are presented in Appendix A.

The data for K exchange with (Ca+Mg) in both soils in the presence of Na and using the miscible displacement method are presented in Table 4. This was used to calculate \hat{E}_{K} as a function of E_{K} as presented in Figures 2a, b together with the binary data. Preference of K over (Ca+Mg) was found regardless of Na presence. The calculated EPR values as a function of PAR_i in the ternary system are presented together with the binary data (Figures 3a, b); the ternary experimental data are reasonably described by the calculated line from the binary system. To predict exchangeable K in ternary systems all the cations participating in the exchange reactions have to be taken into account. Assuming a constant CEC comprised of K, Ca, Mg and Na, the following equation can be introduced:

$$q_{\text{K}} = \text{CEC} - [q_{\text{Na}} + 2(q_{\text{Ca}} + q_{\text{Mg}})] \quad (5)$$

If the Gapon selectivity coefficients which were obtained in the binary system hold in the ternary system, the following equation is obtained:

$$q_{\text{K}} = \frac{\text{CEC } k_{\text{GK}} \text{ PAR}_i}{\text{PAR}_i k_{\text{GK}} + k_{\text{GNa}} \text{ SAR}_{i-1}} \quad (6)$$

A complete description of the mathematical steps to obtain Eq. (6) is given in Appendix B.

The predicted values of exchangeable K (q_{K}) using Eq. (6) were compared with the measured q_{K} values and linear relationships were obtained for both soils (Figures 5a, b). Most of the predicted points lie near the 1:1 line but there is a slight underestimation of q_{K} by the prediction method. The underestimation of q_{K} by the model is due to the underestimation of EPR and probably to the assumption of a constant CEC. The standard deviation in

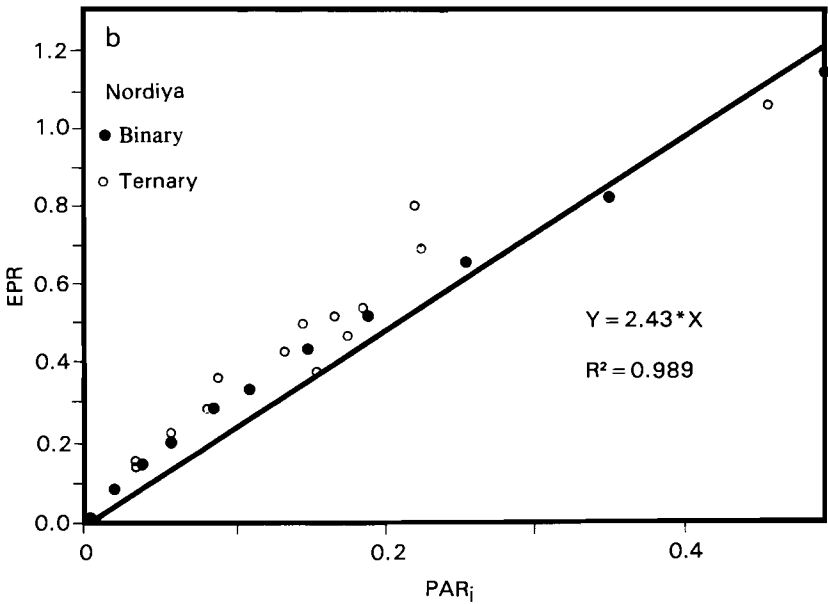
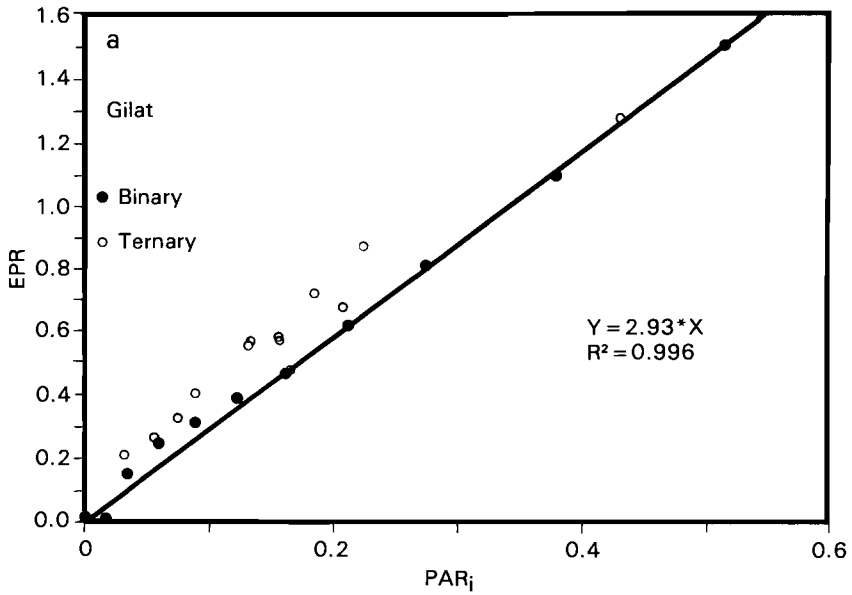


Figure 3. Exchangeable potassium ratio (EPR) as a function of solution K ionic ratio (PAR_i) in binary and ternary systems.

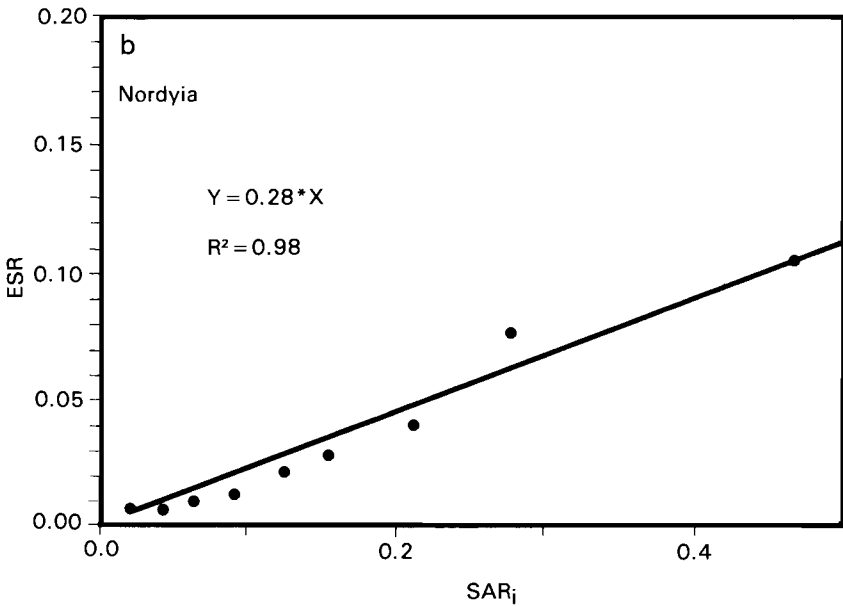
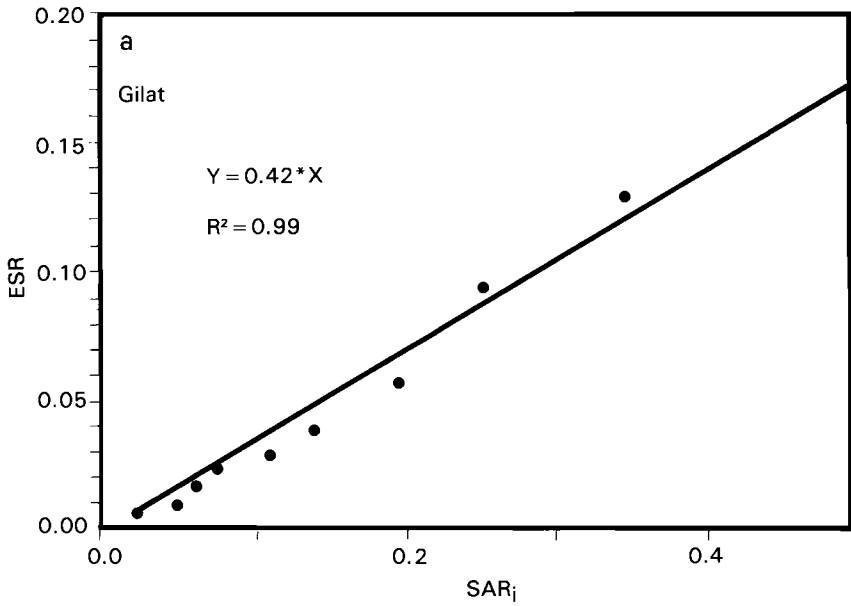


Figure 4. Exchangeable sodium ratio (ESR) as a function of solution ionic ratio (SAR_i).

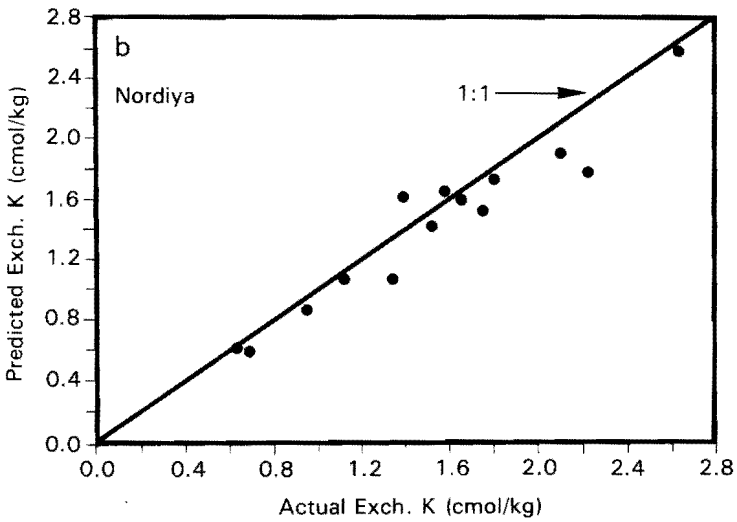
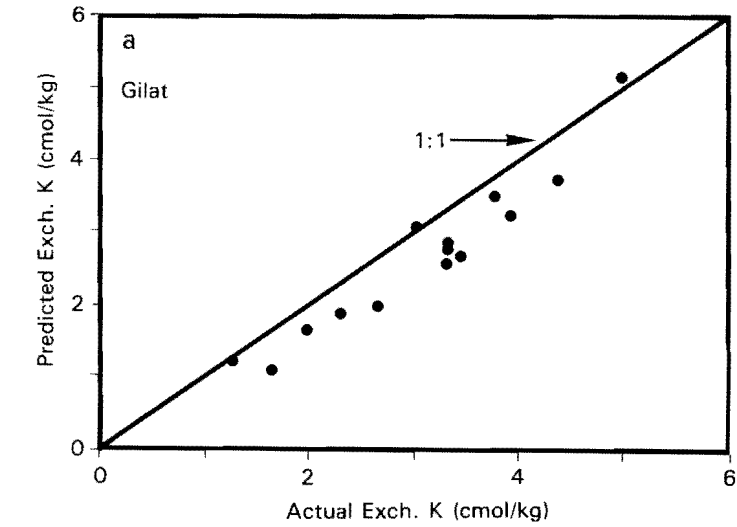


Figure 5. Predicted exchangeable K in «ternary» system using the Gapon model and coefficients obtained from the «binary» systems, versus the measured exchangeable K in the «ternary» system.

determining the CEC of the Gilat and Nordiya soils was 8.3–9.5% of their values, respectively. An overestimation of the CEC value in the ternary system could have led to the underestimation of q_K by the model, since the model is based on an assumption of a constant CEC.

4. Conclusions

From these studies the following conclusions can be drawn:

- (i) K fertilization increased corn yield in all salinity levels only in Nordiya soil and reduced the ratio of Na:K in plant tissue in both soils.
- (ii) A linear relationship between exchangeable potassium percent (EPP) and potassium adsorption ratio (PAR) was obtained in both soils, regardless of salinity level or SAR value.
- (iii) Potassium preference over the divalent cations (Ca + Mg), was found in both soils, regardless of the experimental method and Na concentration.
- (iv) A simple mathematical solution of the Gapon binary equations for K-(Ca + Mg) and Na-(Ca + Mg), in combination with an assumption of a constant CEC, was used successfully to predict the amount of exchangeable K as a function of solution composition.

5. References

- Bar-Tal, A., Feigenbaum, S. and Sparks, D. L.*: Potassium-salinity interactions. *Irrig. Sci.*, in press (1990)
- Beckett, P. H. T.*: Potassium potential, a review. *Potash Rev.* 5/30, 1–41 (1971)
- Bolt, G. H.*: Soil chemistry. B. Physico-chemical models. In: *G. H. Bolt* (Ed.). *Development in Soil Science Series*. Elsevier Publ., Amsterdam-Oxford-New York (1971)
- Carson, C. D. and Dixon, J. B.*: Potassium selectivity in certain montmorillonite soil clays. *Soil Sci. Soc. Am. Proc.* 36, 838–843 (1972)
- Chu, S. Y. and Sposito, G.*: The thermodynamics of ternary cation exchange systems and the subregular model. *Soil Sci. Soc. Am. J.* 45, 1084–1089 (1981)
- Elprince, A. M., Vanselow, A. P. and Sposito, G.*: Heterovalent, ternary cation exchange equilibria: NH_4 -Ba-La exchange on montmorillonite. *Soil Sci. Soc. Am. J.* 44, 964–969 (1980)
- Feigenbaum, S.*: Potassium distribution in a sandy soil exposed to leaching with saline water. *Proc. 13th Congr. Int. Potash Institute, Bern*, 155–162 (1986)
- Feigenbaum, S. and Meiri, A.*: The effect of potassium fertilization on cotton response and potassium distribution under irrigation with saline water. *BARD report I-630-83*, pp. 88–110 (1988)
- Feigenbaum, S., Bar-Tal, A., Portnoy, R. and Sparks, D. L.*: Binary and ternary exchange of potassium on calcareous montmorillonite soils. *Soil Sci. Soc. Am. J.* 54, in press (1990)
- Feigin, A.*: Fertilization management of crops irrigated with saline water. *Plant and Soil* 89, 285–299 (1985)
- Gapon, E. N.*: On the theory of exchange adsorption in soil. *U.S.S.R. J. Gen. Chem.* 3, 144–163 (1933)

- Helal, H. M. and Mengel, K.*: Nitrogen metabolism of young barley plants as affected by NaCl salinity and potassium. *Pl. and Soil* 51, 547-562 (1979)
- Jardine, P. M. and Sparks, D. L.*: Potassium-calcium exchange in a multireactive soil system: II. Thermodynamics. *Soil Sci. Soc. Am. J.* 48, 45-50 (1984)
- Jensen, H. E.*: Potassium-calcium exchange on a montmorillonite and a kaolinite clay: I. A test on the Argersinger thermodynamic approach. *Agrochimica* 17, 181-189 (1973)
- Läuchli, A. and Stelter, W.*: Salt tolerance of cotton genotypes in relation to K/Na selectivity. In: *San Pietro, (Ed.)*. Biosaline Research: A look to the future. Plenum Press, New York, pp. 511-514 (1982)
- McLean, E. D. and Watson, M. E.*: Soil measurements of plant available potassium. In: *R. D. Munson (Ed.)*. Potassium in Agriculture. ASA-CSSA-SSSA, Madison, WI., USA, 277-308 (1985)
- Mengel, K. and Kirkby, E. A.*: Potassium in crop production. *Adv. Agron.* 59-110 (1980)
- Sadusky, M. C., Sparks, D. L., Noll, M. R. and Hendricks, G. J.*: Kinetics and mechanisms of potassium release from sandy Middle Atlantic Coastal Plain Soils. *Soil Sci. Soc. Am. J.* 51, 1460-1465 (1987)
- SAS Institute*: SAS users' guide: Statistics. Version 5. Raleigh, North Carolina (1985)
- Schwertmann, U.*: Die selektive Kationensorption der Tonfraktion einiger Böden aus Sedimenten. *Z. Pfl. Ernähr. Düng. Bodenk.* 97, 9-25 (1962)
- Seyfried, M. S., Sparks, D. L., Bar-Tal, A. and Feigenbaum, S.*: Kinetics of Ca-Mg exchange on soil using a stirred-flow reaction chamber. *Soil Sci. Soc. Am. J.* 53, 406-410 (1989)
- Sparks, D. L.*: Potassium dynamics in soil. *Adv. Soil. Sci.* 6, 1-63 (1987)
- Sposito, G.*: The thermodynamics of the soil solution. Oxford University Press, New York (1981)
- Sposito, G. and Mattigod, S. V.*: On the chemical foundation of the sodium adsorption ratio. *Soil Sci. Soc. Am. J.* 41, 323-329 (1987)
- Thellier, C. and Sposito, G.*: Quaternary cation exchange on Silver Hill illite. *Soil Sci. Soc. Am. J.* 52, 979-985 (1988)
- US Salinity Lab. Staff*: Diagnosis and improvement of saline and alkali soils. In: *L. A. Richards (Ed.)*. Handbook U.S. Dept. Agric. No. 60 (1954)
- Woodruff, C. M.*: The energy of replacement of calcium by potassium in soils. *Proc. Soil Sci. Soc. Am.* 19, 30-40 (1955)

Appendix A

The EPR power values were added to the model until the level of significance did not exceed 0.15. The following equations were obtained:

Nordiya soil:

$$k_{GK} = 5.668 - 15.673EPR + 33.278EPR^2 - 33.353EPR^3 + 12.222EPR^4 \quad 0 < EPR < 1.12 \quad (A_1)$$

$$k_{GK} = 2.23 \quad EPR = 1.12$$

Gilat soil:

$$k_{GK} = 6.577 - 16.755EPR + 27.153EPR^2 - 18.656EPR^3 + 4.609EPR^4 \quad 0 < EPR < 1.5 \quad (A_2)$$

$$k_{GK} = 2.89 \quad EPR = 1.5$$

Appendix B

If the Gapon selectivity coefficients which were obtained in the binary system hold in the ternary system, the unknown values q_{Na} and $q_{Ca} + q_{Mg}$ in Eq. (5) can be replaced by the known solution composition values using Eqs. (3) and (4) (the modified Gapon model), and the following equation is obtained:

$$q_K = CEC - \frac{q_K k_{GNa} SAR_i}{k_{GK} PAR_i} - \frac{q_K}{k_{GK} PAR_i} \quad (B_1)$$

where the k_G values are coefficients that are functions of EPR and ESR according to Eqs. (3-4). Equation (5) was rearranged to calculate q_K :

$$q_K = \frac{CEC k_{GK} PAR_i}{PAR_i k_{GK} + k_{GNa} SAR_i - 1} \quad (B_2)$$