Reprinted from the *Journal of Environmental Quality*
Volume 25, no. 4, July–August 1996, Copyright © 1996, ASA, CSSA, SSSA
677 South Segoe Rd., Madison, WI 53711 USA

Extractable Potassium and Soluble Calcium, Magnesium, Sodium, and Potassium in Two Whey-Treated Calcareous Soils

C. W. Robbins,* C. L. Hansen, M. F. Roginske, and D. L. Sorensen

ABSTRACT

Cheese whey contains 1.0 to 1.4 g K kg^{-1} and 5.0 to 10.0 g total salts kg^{-1} (electrical conductivity [EC] of 7 to 15 dS m^{-1}) and has a pH of 3.3 to 4.6. Much of the 38 × 10^9 L of whey produced in the USA each year is applied to soils. Whey application effect on the K and salinity status of irrigated calcareous soils has not been documented. Objectives of this study were to measure soil pH, sodium adsorption ratio (SAR), saturation paste extract (EC_e), and extractable Ca, Mg, Na, and K changes due to whey application to irrigated calcareous soils at different whey rates and different times of the year. Whey was applied to two calcareous Portneuf silt loam (coarse-silty, mixed, mesic, Durixerollic Calciorthids) soils and a calcareous Nibley silty clay loam (fine, mixes, mesic Aquic Argiustolls) soil at rates up to 2200 m^3 ha^{-1}. These treatments added up to 1050 kg Ca, 200 kg Mg, 790 kg Na, and 2200 kg K ha^{-1} during winter-time, growing season, or year-round whey application. Soil bicarbonate-extractable K increased to more than 500 mg K kg^{-1} in the surface 0.3 m at the highest whey rates and may induce grass tetany in livestock grazed on high whey-treated pastures. Soil K did not increase below 0.6 m in any treatment. Soil pH and SAR were not affected sufficiently to be of concern under these conditions. The EC_e increased to nearly 2.0 dS m^{-1} in the surface 0.3 m under the highest whey rates and would likely affect salt-sensitive crop yields. After a 1-yr whey application rest period under irrigated alfalfa (*Medicago sativa* L.), the EC_e levels returned to background levels.

DURING THE MANUFACTURING of cheese and cottage cheese from milk, about 9 kg of whey is produced with each kilogram of cheese. Total whey production in the USA was about 38 × 10^9 L (10 × 10^9 gal) in 1993 (National Agricultural Statistics Service, 1994, p. 308–309). In Idaho, whey production increased from 0.48 × 10^9 L (0.13 × 10^9 gal) in 1989 to 1.1 × 10^9 L (0.29 × 10^9 gal) in 1993, and is expected to continue to increase (Idaho Agricultural Statistics Service, 1994, p. 31–32).

A considerable fraction of the whey produced is beneficially used directly as animal feed and fertilizer replacement, or dehydrated for use as animal and human food. Not all whey produced by the cheese manufacturing industry can be beneficially used. For economic and logistic reasons it is often necessary to waste the whey for short periods, and land application is usually the most practical treatment method when the wastewater treatment site is properly managed. Due to current and projected cheese and butter production increases in southern Idaho and northern Utah, plus the need for economically and environmentally acceptable whey disposal choices, the various environmental and health regulatory agencies need better information on the fate of whey components as it is treated, or used by land application on calcareous soils. Cheese whey contains considerable quantities of Ca, Mg, Na, and especially K (Table 1) (Jones et al., 1993b; Robbins and Lehrsch, 1992). These high salt concentrations can be beneficial or detrimental to soils, depending on application rates and soil types.

Properly applied whey of all kinds can improve soil physical and chemical properties. Aggregate stability and infiltration rates were increased when whey was applied to acid (Kelling and Peterson, 1981; Watson et al., 1977), calcareous (Lehrsch et al., 1994) and sodic (Jones et al., 1993a) soils. Acid whey from cottage cheese manufactured using phosphoric acid (acid whey) was shown to be beneficial in reclaiming unproductive sodic soils by lowering the soil pH, exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR), without increasing the soluble salt levels (Jones et al., 1993b; Robbins and Lehrsch, 1992). Bicarbonate-extractable K, a method for estimating plant-available K (Gavlak et al., 1994, p. 31–32) was not measured in those studies.

The salt added to the soil by land application of whey is a concern to regulatory agencies and by application site managers. The effects of high K application and movement of added salts (Table 1) have not been adequately documented for whey applied to calcareous soils. The K would not be expected to move below the crop root zone from reasonable to high whey application rates (Robbins and Carter, 1983) but this has not been verified. When ruminants graze grasses grown on soils with molar exchangeable soil K/Mg ratios in excess of 0.5:1 to 1:1, grass tetany (hypomagnesemia) a metabolic disorder, livestock deaths become a potential threat (Mayland and Grunes, 1979). High K applications to grass pastures or range lands could aggravate this imbalance, increasing livestock nutrition problems (Robbins and Mayland, 1993) in an area that already has high K/Mg pasture and rangeland soils (Robbins, 1984).

This paper describes the changes in saturation paste pH, saturation paste extract Ca, Mg, Na, and K concentration, EC_e and SAR (Robbins and Wiegand, 1990) and bicarbonate-extractable K (Gavlak et al., 1994, p. 31–32) in two calcareous soils from three studies. Whey application rates and times of year were the study variables.

MATERIALS AND METHODS

The bicarbonate-extractable K and soil salinity data reported in this paper are from three studies where two kinds of whey were applied to two calcareous soils at different times of the

C.W. Robbins, USDA-ARS, Northwest Irrigation and Soils Res. Lab., 3793 North, 3600 East, Kimberly ID 83341-5076; C.L. Hansen, Dep. of Nutrition and Food Science, Utah State Univ., Logan, UT 84322-8700; M.F. Roginske, and D.L. Sorensen, Dep. of Civil and Environmental Engineering, Utah State Univ., Logan, UT 84322-8200. USDA-ARS in cooperation with Dep. of Nutrition and Food Science and Dep. of Civil and Environmental Engineering, Utah State University. Received 13 June 1995. *Corresponding author (robbins@kimberly.ars.pn.usbr.gov).

Published in J. Environ. Qual. 25:791–795 (1996).

Abbreviations: EC, electrical conductivity; EC_e, saturation paste extract electrical conductivity; SAR, sodium adsorption ratio; ESP, exchangeable sodium percentage; COD, chemical oxygen demand.

Table 1. Typical whey composition.

	"Sweet" whey	"Acid" whey
Water	92%	92%
Total solids	8%	8%
COD†	5%	5%
pH	3.8–4.6	3.3–3.8
Electrical conductivity	7–12 dS m^{-1}	7–8 dS m^{-1}
	mg kg^{-1}	
Total N	900–2200	900–2200
Total P	300–600	1100
Calcium	430–1100	840
Magnesium	90–120	100
Sodium‡	360–1900	600
Potassium	1000–1400	1000–1400
SAR‡	4–16	3–4

† COD is the Chemical Oxygen Demand.
‡ The sodium concentration and the sodium adsorption ratio (SAR) vary with the amount of salt used in the various cheese manufacturing processes and the fraction that ends up in the whey.

year. Studies 1 and 2 were conducted in south central Idaho. Study three was conducted north of Logan, UT.

Studies 1 and 2 each consisted of two annual applications of 0, 20, 40, and 80 mm (0, 200, 400, and 800 m^3 ha^{-1}) of a creamed cheese and mozzarella cheese whey mix to calcareous Portneuf silt loam (coarse-silty, mixed, mesic, Durixerollic Calciorthids) soils. Each set of treatments was applied in a randomized block design, replicated three times. The creamed cheese process uses H_3PO_4 (to coagulate the milk proteins) that ends up in the whey while the mozzarella whey is produced by a biological culture process. Whey application dates and rates and total K applied are shown in Table 2. The K concentrations in this whey source were quite variable from one load to the next. The whey Ca and Mg concentrations were more consistent from one load to the next. Each whey application applied 131 $\pm$ 23 kg Ca ha^{-1} and 19 $\pm$ 4 kg Mg ha^{-1} for a total of 0, 262, 524, and 1048 kg Ca ha^{-1} and 0, 38, 76, and 152 kg Mg ha^{-1} for the study period. Sodium applications were 310 $\pm$ 51 kg Na ha^{-1} the first year and 238 $\pm$ 23 kg Na ha^{-1} the second. This change in Na was probably due to a change in the cheese plant operation. The final total Na application rate for the two studies was 0, 548, 1096, and 2192 kg Na ha^{-1}. The average whey SAR for the first year was 12 and dropped to 7 the second year. Whey SAR was calculated on the total cation analysis since whey rapidly decomposes in the soil (Jones et al., 1993a).

Winter wheat (*Triticum aestivum* L. cv. Malcolm) was planted on 15 Sept. 1992 and again on 20 Sept. 1993. After planting, the plots were furrowed for the whey application and then dikes were made around each plot to contain the whey, irrigation water, and precipitation. Study one treatments were applied during the winters and study two treatments were applied during the wheat growing seasons in 20 mm (200 m^3 ha^{-1}) depth increments (Table 2). The total precipitation between 1 Sept. 1992 and 1 Sept. 1993 was 345 mm (13.6 in) and from 1 Sept. 1993 to 1 Sept. 1994 was 185 mm (7.3 in). The plots were sprinkler irrigated twice in 1993 (for a total of 130 mm or 5.2 in) and three times in 1994 (for a total of 220 mm or 8.7 in) as needed for maximum crop production. On 10 Apr. 1995, the plots were lightly cultivated, planted to alfalfa, and furrowed for surface irrigation. No additional whey treatments were applied. The alfalfa was harvested on 27 June, 3 August, and 26 September. Each alfalfa crop was irrigated once.

On 2 Sept. 1994, and again on 28 Sept. 1995, four 75 mm diam. soil samples were taken from each plot at 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m and the four samples from each depth were mixed and a 5-kg subsample was saved and analyzed. Soil pH was measured in the saturation pastes, EC_e, Ca, Mg, Na, and K were measured in the saturation paste extracts (Robbins and Wiegand, 1990), and plant-available K was estimated using 1:20 sodium bicarbonate extracts (Gavlak et al., 1994, p. 31–32).

Study three consisted of applying swiss cheese whey to a calcareous Nibley silty clay loam (fine, mixed, mesic Aquic Argiustolls) soil. The plots were established in an existing alfalfa field north of Logan, UT. The treatments were applied in a completely randomized design, replicated three times. The whey was surface applied over a 15-mo period in 20 mm (200 m^3 ha^{-1}) increments on the dates shown in Table 3. The whey contained 955 $\pm$ 50 mg K kg^{-1}, for total applications of 0, 600, 1200, and 2200 kg K ha^{-1}. The Ca concentration was 437 $\pm$ 62 mg Ca kg^{-1} whey, and added 0, 261, 522, and 975 kg Ca ha^{-1}. The Mg concentration was 89 $\pm$ 5 mg Mg kg^{-1} whey, adding 0, 53, 107, and 196 kg Mg ha^{-1}. The Na concentration was 360 $\pm$ 43 mg Na kg^{-1} whey, which resulted in applications of 0, 216, 432, and 792 kg Na ha^{-1}. The average whey SAR was 4.1 for this study.

Irrigation water (about 500 mm) was applied by surface flood irrigation during the 1993 growing season. No irrigation water was applied in 1994 prior to sampling on 7 June 1994. A total of 735 mm of precipitation was measured by the Utah Climate Center on the Utah State University campus, Logan, UT, for the period of the study. The Climate Center data collection site is 0.6 km northeast of the study site. The irrigation plus precipitation for the study period was approximately 1250 mm.

On 7 June 1994, all plots were sampled from 0 to 0.30 and 0.30 to 0.60 m. Four 75 mm diam. soil samples were taken from each depth in each plot, mixed and 5-kg subsamples were saved and analyzed as described for Studies 1 and 2.

Table 2. Whey application dates and whey and K application rates for Studies 1 and 2.

	Study 1, winter-time application								
Whey depth	8 Dec. 1992	19 Jan. 1993	2 Mar. 1993	20 Apr. 1993	30 Nov. 1993	28 Dec. 1993	27 Jan. 1994	22 Feb. 1994	Total
mm		kg K ha^{-1}							
0									0
40			290			195			485
80		255		333	177		248		1013
160	310	255	290	333	177	195	248	282	2090
	Study 2, growing season application								
	18 May 1993	8 June 1993	28 June 1993	21 July 1993	10 May 1994	31 May 1994	22 June 1994	12 July 1994	
0									0
40		241				213			454
80	195		250		252		284		981
160	195	241	250	219	252	213	284	255	1909

Table 3. Whey application dates and depths and total K added for Study 3.

Total whey	14 Jan. 1993	18 Feb. 1993	29 Mar. 1993	22 July 1993	16 Aug. 1993	30 Sept. 1993
	mm					
0						
60	20			20		
120	20	20		20		20
220	20	40	20	20	20	20

Total whey	18 Nov. 1993	27 Jan. 1994	25 Feb. 1994	25 Mar. 1994	Total K added
	mm				$kg\ ha^{-1}$
0					0
60		20			600
120		20		20	1200
220	20	20	20	20	2200

RESULTS

Potassium is usually considered a fertilizer element and will be discussed separately from the data used to evaluate the salinity hazards of land applied whey.

Potassium

Bicarbonate-extractable K levels for most field crops in the northwestern USA are considered low below 100, marginal between 100 and 120 and adequate above 120 mg K kg^{-1} soil. Comparable potato (*Solanum tuberosum* L.) K values are 1.5 to 2 times higher (Lamborn, 1975).

Study 1

The bicarbonate-extractable K in the untreated soil surface 0.3 m was marginal for crop production, but the 40 mm (485 kg K ha^{-1}) treatment increased K to acceptable concentrations for most crops even though it was not significantly different from the untreated plots (Table 4). The 80 and 160 mm (1013 and 2090 kg K ha^{-1}) treatments significantly increased the bicarbonate-extractable K levels in the surface 0.3 m. Only the highest whey rate significantly increased the bicarbonate-extractable K in the 0.3 to 0.6 depth. There was not a significant increase in bicarbonate-extractable K in the 0.6 to 0.9 m depth. Saturation paste extract K was increased in only the surface 0.3 m and only by the two highest whey applications. Recovery of the applied K from the top 0.9 m of soil by the bicarbonate extractant varied from 32% for the low K application treatment to 80% in the highest K application treatment.

Study 2

The untreated, growing season applied whey plots were low in plant-available K (lower than the winter-time applied plots) in the 0.0 to 0.3 m depth and the total amount of K applied to the growing season plots was slightly less (Tables 2 and 4). The 40 mm (454 kg K ha^{-1}) treatment increased K to acceptable concentrations for most crops even though it was not significantly different from the untreated plots (Table 4). The 80 and 160 mm (981 and 1909 kg K ha^{-1}) treatments significantly increased the bicarbonate-extractable K levels in the surface 0.3 m. Only the highest whey rate significantly increased the bicarbonate-extractable K in the 0.3 to 0.6 depth. There was not a significant increase in bicarbonate-extractable K in the 0.6 to 0.9 m depth. Recovery of the applied K from the top 0.9 m of soil by the bicarbonate extractant varied from 73 to 86%.

Saturation extract K concentrations were increased in the surface 0.3 m by the 80 and 160 mm whey treatments and the 160 mm treatment increased the K in the 0.3 to 0.6 m depth. There was not a significant increase in the saturation extract K concentration in the 0.6 to 0.9 sampling depth.

The initial bicarbonate-extractable levels in the second

Table 4. Study 1 (winter-time whey application) and Study 2 (growing season whey application) bicarbonate and saturation paste-extractable K concentrations by depth and treatments and percentage applied K recovered in the bicarbonate extracts.

Total K applied	Bicarbonate-extractable K 0.0–0.3 m	0.3–0.6 m	0.6–0.9 m	Saturation paste-extractable K 0.0–0.3 m	0.3–0.6 m	0.6–0.9 m	Bicarb K recovery
Winter-time application							
$kg\ ha^{-1}$	$mg\ kg^{-1}$			$mmol\ L^{-1}$			%
0	101 a*	17 a	22 a	0.13 a	0.06 a	0.01 a	
485	141 a	18 a	27 a	0.20 a	0.05 a	0.01 a	32
1013	302 b	24 ab	26 a	0.61 b	0.05 a	0.01 a	68
2090	551 c	39 b	38 a	1.22 b	0.11 a	0.02 a	80
Growing season application							
	0.0–0.3 m	0.3–0.6 m	0.6.0–0.9 m	0.0–0.3 m	0.3–0.6 m	0.6–0.9 m	
	$mg\ kg^{-1}$			$mmol\ L^{-1}$			%
0	76 a	36 a	19 a	0.06 a	0.06 a	0.01 a	
454	159 a	63 ab	20 a	0.23 a	0.04 a	0.01 a	83
981	313 b	59 ab	20 a	1.14 b	0.11 ab	0.01 a	73
1909	506 c	84 b	27 a	1.53 b	0.25 b	0.01 a	86

* Numbers in a column of four values followed by the same letter are not different at the $P \leq 0.05$ level.

Table 5. Study 3 bicarbonate and saturation paste-extract K concentration by depths and treatments and percent applied K recovered in the bicarbonate extracts.

Total K applied	Bicarbonate-extractable K 0.0–0.3 m	0.3–0.6 m	Saturation paste-extractable K 0.0–0.3 m	0.3–0.6 m	Bicarb K recovery
kg ha^{-1}	mg kg^{-1} soil		m mol L^{-1}		%
0	232 a*	176 a	0.14 a	0.23 a	
600	281 ab	180 a	0.21 ab	0.17 a	30
1200	340 b	220 a	0.39 ab	0.13 a	42
2200	539 c	222 a	0.67 b	0.26 a	53

* Numbers in a column followed by the same letter are not different at the $P \leq 0.05$ level.

depth increment for the growing season were initially higher than the winter-time plots, and the increases in the second depth were greater for the growing season treated plots. Other than this exception, there did not appear to be a seasonal application difference effect between these two studies.

Study 3

The lowest whey application rate did not increase the bicarbonate-extractable K significantly in the 0.0 to 0.3 m depth of this soil that contained adequate plant-available K (Table 5). The 120 and 220 mm (1200 and 2200 kg K ha^{-1}) whey application rates increased the bicarbonate-extractable K in the surface 0.3 m depth increment. Bicarbonate-extractable K did not increase significantly in the 0.3 to 0.6 m soil depth. Recovery of the applied K from the top 0.9 m of soil by the bicarbonate extractant varied from 30% for the low K application treatment to 53% in the highest K application treatment. Even though higher K application rates were applied in Study 3, the final bicarbonate extractable values for the two higher rates were about the same as those found in Studies 1 and 2.

Saturation-extract K concentrations were significantly increased only in the 0.0 to 0.3 depth by the highest K application rate.

Table 6. Study 1 (winter-time whey application) 1994 saturation paste pH; EC$_e$ and saturation extract cations and 1995 EC$_e$ values by depth as affected by whey application rates.

Whey application	pH	1994 EC$_e$	1995 EC$_e$	Ca	Mg	Na	SAR
mm		dS m^{-1}		mmol L^{-1}			
			0.0–0.3 m				
0	8.0 a	0.7 a	0.7 a	2.0 a	0.9 a	1.9 a	1.1 a
40	7.9 ab	0.8 a	0.7 a	2.0 a	0.9 a	2.3 ab	1.3 a
80	7.9 ab	1.1 ab	0.8 ab	2.6 a	1.2 a	3.5 ab	1.8 a
160	7.8 b	1.8 b	0.9 b	3.9 b	1.6 a	6.0 b	2.5 b
			0.3–0.6 m				
0	8.2 a	0.7 a	0.7 a	1.5 a	0.9 ab	2.0 a	1.3 a
40	8.1 a	0.7 a	0.7 a	1.4 a	0.9 ab	2.8 ab	1.9 ab
80	8.1 a	0.9 a	0.7 a	1.6 a	0.7 b	3.9 b	2.6 b
160	8.0 a	1.3 b	0.8 a	1.9 a	1.1 a	6.5 c	3.7 c
			0.6–0.9 m				
0	8.1 a	0.4 a	0.5 a	1.0 a	0.9 a	1.5 a	1.1 a
40	8.0 a	0.4 a	0.5 a	1.2 a	1.1 a	1.8 a	1.2 a
80	8.0 a	0.5 a	0.5 a	0.9 a	0.6 b	2.0 a	1.7 ab
160	8.0 a	0.6 a	0.6 a	0.8 a	0.6 b	2.9 b	2.4 b

Numbers in a column of four values followed by the same letter are not different at the $P \leq 0.05$ level.

Table 7. Study 2 (growing season whey application) 1994 saturation paste pH, EC$_e$, and saturation-extract cations and 1995 EC$_e$ values by depth as affected by whey application rates.

Whey application	pH	1994 EC$_e$	1995 EC$_e$	Ca	Mg	Na	SAR
mm		dS m^{-1}		mmol L^{-1}			
			0.0–0.3 m				
0	7.9 a*	0.9 a	0.9 a	2.2 a	1.2 a	3.5 a	1.9 a
40	7.8 a	1.1 a	0.9 a	3.0 ab	1.4 a	3.7 a	1.8 a
80	7.7 ab	1.7 b	1.0 ab	4.3 b	2.0 b	5.1 ab	2.0 a
160	7.6 b	1.9 b	1.1 b	4.4 b	2.1 b	6.8 b	2.6 a
			0.3–0.6 m				
0	8.0 a	0.8 a	0.8 a	2.1 a	1.1 a	2.4 a	1.4 a
40	7.9 a	1.1 ab	0.9 a	2.1 a	1.5 a	4.3 ab	2.2 b
80	7.8 a	1.6 b	1.0 a	3.1 b	2.1 ab	5.8 b	2.4 bc
160	7.7 a	2.5 c	0.9 a	5.4 c	3.6 b	8.8 c	2.9 c
			0.6–0.9 m				
0	8.2 a	0.6 a	0.6 a	0.9 a	0.8 a	2.2 a	1.7 a
40	8.0 a	0.6 a	0.7 a	1.0 a	0.8 a	2.4 ab	1.6 a
80	8.0 a	0.8 ab	1.0 b	1.2 ab	1.0 a	3.4 bc	2.5 a
160	8.0 a	1.1 b	1.0 b	1.8 b	1.4 b	4.2 c	2.3 a

* Numbers in a column of four values followed by the same letter are not different at the $P \leq 0.05$ level.

pH, Soil Salinity, and SAR

Saturation paste pH values were decreased very slightly in the surface 0.3 m of both Portneuf soils by the highest whey treatment (Tables 6 and 7), but pH values in the Nibley soil were not significantly affected by the acidic nature of the whey (Table 8). Both soils contain calcium carbonate (lime).

The EC$_e$ values were increased in the surface 0.3 m by the highest rate in Study 1 (Table 6), the two highest rates in Study 2 (Table 7), and by all three treatments in Study 3 (Table 8). Those treatments that increase the EC$_e$ above 1.0, add sufficient salt to cause yield reductions in salt-sensitive crops during the application period growing season, but for crops such as barley (*Hordeum vulgare* L.), sugarbeet (*Beta vulgaris* L.), or alfalfa, yield reductions would not be expected (Bresler et al., 1982). The added soluble salts were essentially leached out of Studies 1 and 2 profiles over the next year by winter precipitation and the irrigation water applied to the alfalfa in 1995 (Tables 6 and 7). Saturation-extract Ca, Mg, and Na concentrations essentially followed the EC$_e$ trends (Tables 6, 7, and 8).

The saturation-extract SAR values were increased

Table 8. Study 3 saturation paste pH, EC$_e$, and saturation extract cations by depth as affected by whey application rates.

Whey application	pH	EC$_e$	Ca	Mg	Na	SAR
mm		dS m^{-1}	mmol L^{-1}			
			0.0–0.3 m			
0	8.1 a*	0.6 a	1.5 a	1.7 a	0.4 a	0.2 a
60	8.2 a	0.7 b	1.6 a	2.0 b	0.9 b	0.5 b
120	8.1 a	0.8 c	1.8 ab	2.0 b	1.4 c	0.7 c
220	8.0 a	1.1 d	2.1 b	2.2 b	1.9 d	0.9 c
			0.3–0.6 m			
0	8.1 a	0.7 a	1.7 a	2.3 a	1.1 a	0.5 a
60	8.2 a	0.7 a	1.5 a	2.2 a	0.9 a	0.5 a
120	8.1 a	0.9 a	1.8 a	2.3 a	1.4 a	0.7 a
220	8.1 a	0.8 a	1.9 a	2.2 a	1.4 a	0.7 a

* Numbers in a column of four values followed by the same letter are not different at the $P \leq 0.05$ level.

slightly, but significant by the highest whey rate down to 0.9 m and the 80-mm treatment in the 0.3 to 0.6 mm increment of Study 1 (Table 6). All three application rates increased the SAR in the 0.3 to 0.6 m depth in Study 2 (Table 7). All whey application rates increased Study 3 0.0 to 0.3 m depth SAR values (Table 8). From a practical standpoint, the limited SAR increases were not a concern. Saturation-extract SAR values of <10 nearly always indicate that Na is not adversely affecting soil physical conditions (Bresler et al., 1982).

CONCLUSIONS

Bicarbonate-extractable K data from these studies suggests that a 40 to 80 mm whey application to these soils increases K to a satisfactory K fertility level for most crops (Lamborn, 1975). If whey is to be applied to grass pastures or range sites with low available Mg, managers should be aware that the high K/Mg ratios in whey present a potential grass tetany threat. The high whey treatments increased the saturation-extract K/Mg in Study 1 from 0.14 to 0.76, in Study 2 from 0.05 to 0.73 and Study 3 from 0.08 to 0.30. If these high saturation-extract K/Mg ratios are converted to exchangeable ratios (Robbins and Carter, 1983), they will exceed the suggested 0.5 to 1.0 values (Mayland and Grunes, 1979) by a factor of 5 to 10.

The whey-applied K does not appear to leach as do the other cations. This is not surprising since on a molar basis K makes up 28% of the cations in the Study 1 and 2 whey and 45% of the cations in the Study 3 whey, while K constitutes only 1.2% of the saturation-extract cations in the Portneuf soil and 2.8% in the Nibley soil. This coupled with the fact that in the Portneuf soil, the selectivity coefficient preference for K over Ca is 10:1, over Mg is 32:1 and over Na is 21:1, calculated on cation concentrations (Robbins and Carter, 1983; Robbins, 1984), would drastically change the solution cation-cation exchange equilibrium. The high K applications would also upset the soil solution-cation exchange-K fixation equilibrium. These three factors act together to retain K in the soil surface at the expense of the other cations until new equilibriums are established. This shows up as substantial but incomplete bicarbonate-extractable K recovery as whey application rates increase (Tables 4 and 5). Unfortunately, similar cation exchange selectivity coefficient data are not available for the Nibley soil, but similar reactions are expected.

Even with the high salt concentration in the whey (EC of 7–12 dS m^{-1}), the dilution and leaching from irrigation water was sufficient to avoid excessive salt build-up in the root zone for the more salt-tolerant crops. Applying undiluted whey to crops by sprinkler irrigation will, however, usually cause foliar burn during hot weather. Yields of salt-sensitive crops such as most vegetables and fruits would probably be decreased by more than about 50 mm per year whey applications (Bresler et al., 1982). After a 1-yr rest period from whey application under irrigated alfalfa, the EC_e levels returned to background levels.

Saturation paste pH values were lowered slightly by the highest whey rates on the Portneuf soil, but not on the Nibley soil. The measured decrease was not sufficient to be of practical importance.

The highest whey rates used here did not produce a sodium hazard (high SAR). Previous work on soils with similar textures and mineralogy to the Portneuf soil suggests that in the presence of high K/Na ratios in the soil solution or added water, Na will be replaced or excluded from the exchange sites and will be less of a concern than in the absence of high K/Na ratios (Robbins and Carter, 1983; Robbins, 1984).

Winter-time whey application effects were not different than growing season applied whey effects with respect to K, pH, salinity, or SAR.

ACKNOWLEDGMENTS

Portions of this research were supported by the Western Center for Protein Research and Technology (formerly the Western Dairy Foods Research Center) and the Utah Water Research Laboratory, both on the Utah State University campus in Logan, UT. Also, thanks to Larry L. Freeborn for conducting most of the chemical and statistical analyses.

REFERENCES

Bresler, E., B.L. McNeal, and D.L. Carter. 1982. Part 3. Management. p. 174–185. *In* Saline and sodic soils principles-dynamics-modeling. Springer-Verlag New York, New York.

Gavlak, R.G., D.A. Horneck, and R.O. Miller. 1994. Plant, soil, and water reference methods for the western region. Western Regional Ext. Publ. 125. Univ. of Alaska Coop. Ext. Service, Fairbanks, AK.

Idaho Agricultural Statistics Service. 1994. Idaho agricultural statistics. Idaho Dep. of Agriculture and U.S. Department of Agriculture, Boise, ID.

Jones, S.B., C.L. Hansen, and C.W. Robbins. 1993a. Chemical oxygen demand fate from cottage cheese (acid) whey applied to a sodic soil. Arid Soil Res. Rehab. 7:71–78.

Jones, S.B., C.W. Robbins, and C.L. Hansen. 1993b. Sodic soil reclamation using cottage cheese (acid) whey. Arid Soil Res. Rehab. 7:51–61.

Kelling, K.A., and A.E. Peterson. 1981. Using whey on agricultural land – A disposal alterative. Ser. no. A3098. Coop. Ext. Program, Univ. of Wisconsin, Madison.

Lamborn, R.E. 1975. Tentative soil test adequacy levels for phosphorus and potassium. p. 195–196. *In* Proceedings, Twenty-sixth annual Pacific Northwest Fertilizer Conference, Salt Lake City, UT. 15–17 July 1975. Northwest Plant Food Assoc., Portland, OR.

Lehrsch, G.A., C.W. Robbins, and C.L. Hansen. 1994. Cottage cheese (acid) whey effects on sodic soil aggregate stability. Arid Soil Res. Rehab. 8:19–31.

Mayland, H.F., and D.L. Grunes. 1979. Soil-climate-plant relationships in the etiology of grass tetany. p. 123–175. *In* V.V. Rendig and D.L. Grunes (ed.) Grass tetany. Spec. Publ. 35. ASA, Madison, WI.

National Agricultural Statistics Service. 1994. Agricultural statistics. USDA, Washington DC.

Robbins, C.W. 1984. Sodium adsorption ratio-exchangeable sodium percentage relationships in a high potassium saline-sodic soil. Irrig. Sci. 5:173–179.

Robbins, C.W., and D.L. Carter. 1983. Selectivity coefficients for calcium-magnesium-sodium-potassium exchange in eight soils. Irrig. Sci. 4:95–102.

Robbins, C.W., and G.A. Lehrsch. 1992. Cottage cheese whey effects on sodic soils. Arid Soil Res. Rehab. 6:127–134.

Robbins, C.W., and H.F. Mayland. 1993. Calcium, magnesium, and potassium uptake by Crested Wheatgrass grown on calcareous soils. Commun. Soil Sci. Plant Anal. 24:915–926.

Robbins, C.W., and C.L. Wiegand. 1990. Field and laboratory measurements. p. 201–219. *In* K.K. Tanji. (ed.) Agricultural salinity assessment and management. ASAE, New York.

Watson, K.S., A.E. Peterson, and R.D. Powell. 1977. Benefits of spreading whey on agricultural land. Water Pollut. Control Fed. 49:24–34.