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Using forages and livestock to manage drainage water in the San Joaquin Valley

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Abstract

Drainage water ($4<$ EC ($\mathrm{dSm^{-1}}$)<20; $10<$ SAR < 40) reuse for production of tolerant forages would provides the means to reduce the drainage volume and affiliated negative impacts of its disposal. To assess the productive potential and sustainability of this strategy, Bermuda grass (*Cynodon dactylon* (L.) Pers.) was established in 2000 and 2001 on a salt-affected and tile drained site (32.4 ha) with a clay loam soil in California's San Joaquin Valley. Using electromagnetic induction (EM) techniques coupled with a spatial statistical program (ESAP v2.0) forty sites were selected that encompassed the heterogeneity of the study area. At these sites soil core samples were taken at 0.3 m intervals to a depth of 1.2 m for chemical and physical analysis. Variation in selected soil chemical properties include: $12.8< EC_e < 36.6$ $\mathrm{dSm^{-1}}$; $28.8<$ SAR< 88.8, and $2.5 <$ clay $< 48.3\%$; $11.5 <$ B< 32.2 mg $\mathrm{L^{-1}}$; $477 <$ Mo < 1960 µg $\mathrm{L^{-1}}$. The salinity and volume of irrigation and drainage water, and forage biomass and quality have been monitored. The leaching fraction averages about 0.13. Forage Mo contents from 1 to 5 mg $\mathrm{kg^{-1}}$ DM, and Cu: Mo ratios averaged 3.3, while forage yield in the establishment year declined with EC_e, and failed to grow above EC_e levels of 22 $\mathrm{dSm^{-1}}$.

Keywords: electrical conductivity, EC_a, drainage water reuse, EM, salinity, Mo, B, forage quality, bermuda grass

Introduction

The Sacramento and San Joaquin Valleys of California are among the most agriculturally productive areas in the world. Because there is no outlet for saline drainage water in the western San Joaquin Valley (WSJV), continued agricultural productivity is threatened in this portion of the valley. The productivity of an estimated 300,000 ha of land is adversely affected by the presence of shallow or perched water (0 to 1.5 m). Without a means of disposing of drainage water, increasing amounts of farmland will become salt impaired. If all lands with shallow water tables were drained, approximately 30,000 ha of land would be needed for evaporation ponds, an amount almost twenty times greater than that currently available. Regulations limit the expansion or development of new evaporation ponds.

An alternative means of reducing drainage water volumes is reuse of drainage water on agricultural lands. Hypotheses about the management and reuse of drainage were developed by Rhoades (1989), Grattan and Rhoades (1990), modeled by Bradford and

Letey (1993) and assessed to be economically favorable by Posnikoff and Knapp (1996). However, agricultural drainage water in the WSJV is sufficiently saline to be detrimental to most crops and often contains toxic trace elements (Deverel and Millard, 1988; Fuji and Swain, 1995) particularly Se, B, and Mo. Se is toxic to shore birds and migratory waterfowl when it concentrates in the food chain of evaporation ponds (Skorupa, 1998). B can reduce plant yields. Mo can cause harmful effects to ruminant animals that eat forages grown on soils that contain as little as 1.5-5.0 mg kg^{-1} total Mo (Barshad, 1948). Accumulation of trace elements in soils and crops to toxic levels would create a new pollution problem, and a failed system.

Maintenance of soil physical properties is another concern. As the level of sodicity increases, greater levels of salinity in irrigation water are required to prevent deterioration of water infiltration and redistribution, and aeration (Oster and Jayawardane, 1998; Quirk, 2001,). Irrigation with saline-sodic drainage water typically found in the WSJV ($6 < EC < 20$ dS m^{-1}; $5 < SAR < 35$) will result in soil salinities ranging from 6 to 60 dSm^{-1} and SARs ranging from 5 to 60 if the leaching fraction (LF) is approximately 30%. Expected levels of salinity in the irrigation water should compensate for increased levels of exchangeable Na. Rainfall poses potential problems with crusting and soil tilth because it can reduce salinities at the soil surface to levels that are insufficient to counteract the effects of exchangeable sodium. Use of drainage water on lands dedicated to the production of perennial grass species, which tolerate high salinities and poor aeration during the winter rainfall season, is a management strategy that can mitigate soil physical problems posed by rainfall. It has the potential for reducing the volume of drainage water and the amount of land needed for its disposal by up to an order of magnitude (Oster, 1997), thereby lowering the cost of disposal and limiting the exposure of wildlife to potentially toxic waters in evaporation ponds. High quality forages for dairy cattle, beef cattle, and sheep are in short supply in the Central Valley of California. Salt-tolerant forages will increase forage supplies.

If the production of high quality forage using drainage water can be coupled economically to livestock enterprises, drainage water would become an asset rather than a problem. The use of forage-livestock systems, together with careful management of a small number of drainage ponds, will address the most serious problem affecting the long-term sustainability of farming in the WSJV.

Materials and Methods

Site preparation and soil quality assessment

To establish the site, a 32.4 ha field was laser leveled to with zero slope north to south and a slope of 0.0009 west to east, and subsurface tile drains were installed at a constant depth of 1.2 m (Figure 1a). The soil is part of the Lethent clay loam series (fine, montmorillanitic, thermic, typic natrargid, USDA, 1986). An interceptor drain with a gravel envelope was installed along the west side of the field. Drainage lines in the paddocks are spaced at 37.5 m and 1.2 m deep using 7.6 cm diameter perforated plastic pipe with a gravel envelope. The central drain serves an area of roughly 13,650 m^2. Aside from a center drain, each 4-ha paddock (75 X 364 m) has drains at the paddock's north and south boundaries, beneath the paddock berms, to ensure that each paddock can be treated as an independent hydrologic unit. Drainage flows and their salinity are monitored on the central drain in paddocks 2, 3, 6, and 7 (Figure 1a).

Initial site characterization occurred in 1999 following an irrigation in July salinity mapping and soil sampling began in August. Geophysical methods developed by Rhoades and colleagues (Rhoades *et al.*, 1999) were used to characterize spatial distributions of soil salinity (Corwin *et al.*, submitted). EC_a was measured non-invasively with mobile EM equipment at 384 sites (Figure 1b) and with a mobilized, tractor-mounted version of an invasive "fixed-array" unit. All measurements were geo-referenced with a global positioning system (GPS). In addition, 0-0.3 m and 0.3-0.6 m EC_a measurements were taken with a shallow four-electrode (Wenner) fixed-array to provide shallow measures of EC_a in contrast to the deeper penetration depth (1.2-1.5 m) of the EM measurements.

Utilizing the EM data and statistical software (ESAP v2.0) developed by Lesch *et al.* (1995), 5 sites within each paddock (40 total) were selected that characterize the spatial variability in EC_a across each paddock. At each of the 40 sites, two or more soil cores were taken at 0.3 m increments to a depth of 1.2 m. One set of soil cores was designated for soil chemical property analysis and the other set for soil physical property analysis. Half of the soil samples were analyzed for PW; EC_e; pH_e; SP; anions (HCO_3^-, Cl^-, NO_3^{--}, SO_4^{--}) and cations (Na^+, K^+, Ca^{++}, Mg^{++}) in the saturation extract; trace elements (B, Se, As, Mo) in the saturation extract; % $CaCO_3$; % gypsum; CEC; exchangeable Na^+, K^+, Mg^{++} and Ca^{++}; ESP; and SAR. The other half of the soil samples designated for analysis of soil physical properties were analyzed for PW, θ_v, ρ_b, and % clay.

All spatial data was entered into a geographic information system (GIS). Maps of the soil properties were prepared by interpolating the measurements at the 40 sample sites using inverse-distance-weighting interpolation. Maps of mobile EM EC_a measurements and shallow four-electrode (Wenner) fixed-array EC_a (0-0.3 and 0.3-0.6 m) measurements were prepared by interpolating the measurements at the 384 measurement sites (Corwin *et al.*, submitted).

Drainage water volume, composition, and leaching

A v-notch weir, instrumented with pressure transducers to measure the water elevation crossing the notch, was installed in a 1.2-m diameter culvert (Schoeneman and Ayars, 1999; Kaffka *et al.*, 2001) located on the east end of center drains in paddocks 2, 3, 6, and 7 (Figure 1a). Data loggers (CR510, Campbell Scientific, Inc) were installed to record the water elevation and the electrical conductivity of the drainage water with a conductivity sensor. With the data obtained it is possible to calculate the volume-weighted salt load in the drainage water. The amount of irrigation water applied and its electrical conductivity is also continuously monitored with a digital flow meter and a conductivity/temperature sensor.

Bermuda grass establishment and sampling

Bermuda grass (*Cynodon dactylon (L>) Pers.*) was established after site assessment during late fall in 1999 and summer of 2000. Cultivar Giant was planted in plots 1 to 4 to allow both grazing and hay making, while cv. Common was planted in plots 5 to 8, for grazing purposes only. Systematic sampling of plots 1 to 4 began in late September of 2000, and of all eight plots in June 2001. Forage was sampled at locations selected initially for soil sampling (Figure 1b). Plant material was collected from two 0.3 m by 1 m grids at each location, placed opposite each other approximately 1 m from the soil sample point. Soil sample points were located using a Trimble GPS system with an accuracy of less than 1 m. At each sampling, forage was collected at a new compass direction, to avoid re-sampling the same site. Sampling in this manner provides an estimate of standing biomass. While sampling, forage height before and after harvest was measured. After drying at 35^0C, the forage samples were ground and analyzed for total N, crude protein, Ash, ADF and NDF, total P, K, S, Ca, Mg, Na, B, Zn, Mn, Fe, Cu, Mo, Se, and Cl.

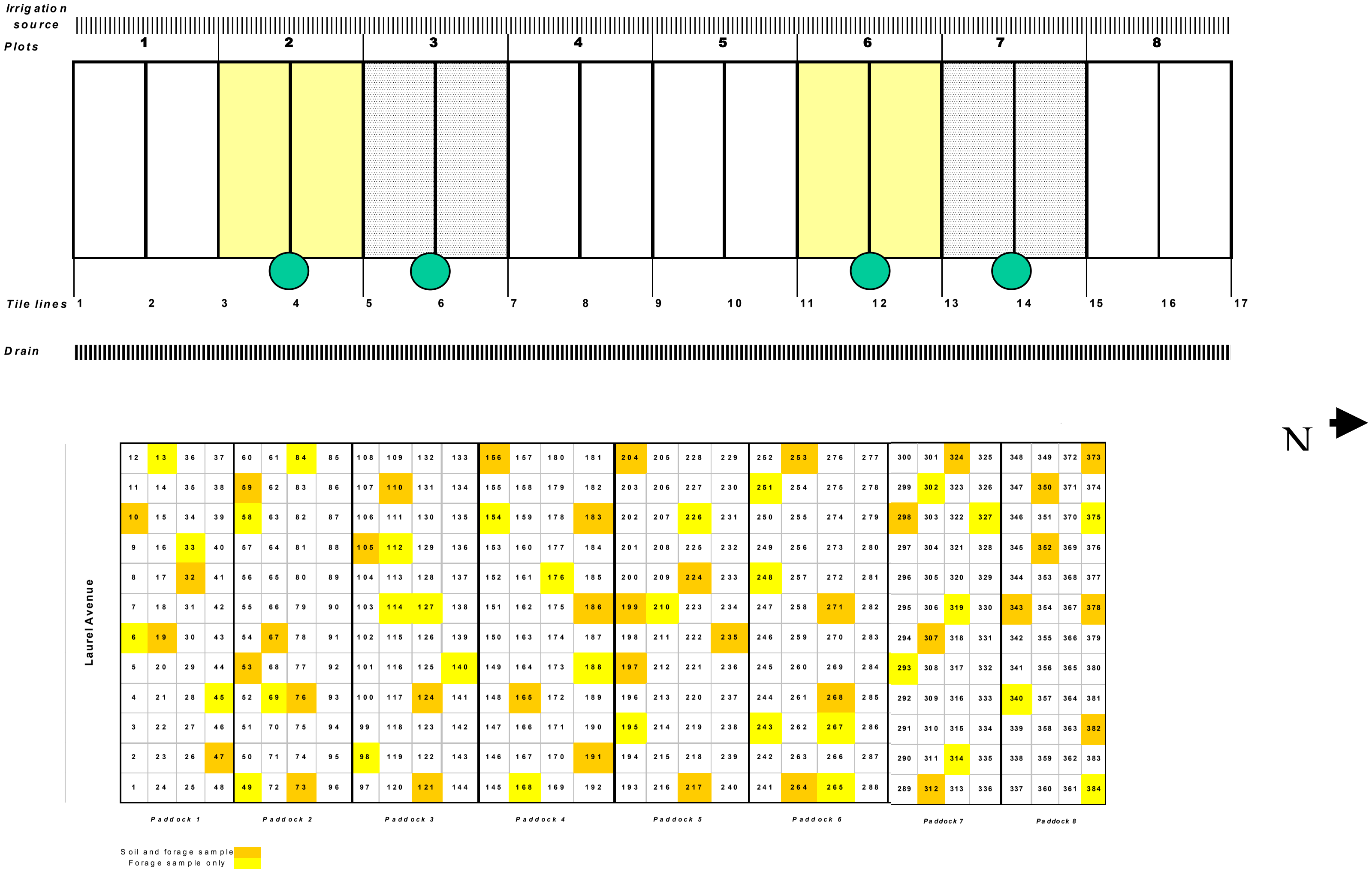
Results and Discussion

Soil salinity, other physico-chemical properties, and salinity

Mapping EC_a measurements provides insights into the three-dimensional distribution of soil salinity. The map (Figure 2) shows a large area of very high EC_a measurements in the southwestern portion of the study area that extends through a substantial portion of paddocks 2, 3, and 4. In addition, a smaller area of high EC_a exists in the northeast primarily spreading through paddocks 6 and 7. In general soil salinity increases with depth (EMh < Emv) with inverted conditions occurring only in two small areas.

The study area is a severely saline-sodic, calcareous-gypsiferous soil that is heavy textured at the surface (0-0.3 m) and has low to very high levels of B and moderate to high levels of Mo (Table 1). There is considerable spatial variability as indicated by the moderately high CV values in Table 1. Typically, water content (either PW or θ_v) increases with depth (Table 1). Bulk density is the lowest in the top depth increment (0-0.3 m) with an average value of 1.29 mg m^{-3}, and then becomes stable for the remaining depths reaching 1.51 mg m^{-3}. pH_e typically averages around 7.5-7.6 for all depths and usually falls within the range of 7-8. Saturation percentage (SP) ranges from less than 40% to over 90% with the greatest range occurring at the bottom depth (0.9-1.2 m). The levels of Se and As are low with Se never exceeding 77 μg L^{-1} and As never exceeding 116 μg L^{-1} at any depth increment. SAR tends to be associated with EC_e and, like EC_e, tend to increase with depth. The association between salinity (EC_e) and the soil chemical properties of Cl^-, SAR, and ESP is reflected by the Pearson correlation coefficients determined for EC_e and Cl^- ($r = 0.76$), EC_e and SAR ($r = 0.95$), and EC_e and ESP ($r = 0.54$) using values for composite soil cores over the depth of 0-1.2 m. CEC correlates well with SP ($r = 0.60$) indicating the influence that clay content has on the properties of CEC and SP. The Pearson correlation coefficient between Mo and B using values for composite soil cores over the depth of 0-1.2 m is $r = 0.59$. In the top depth increment (i.e., 0-0.3 m), Mo and B are positively correlated with salinity with r^2 values of 0.60 and 0.72, respectively. Consequently locations with high salinity may also be locations with forages high in these trace elements.

In general the % clay tends to decrease with depth with an average value of 35.9 % in the 0-0.3 m depth increment decreasing to 23.3% in the 0.9-1.2 m depth increment (Table 1). The higher clay content at the surface will enhance the formation of surface cracks, which will likely serve as conduits for water infiltration before soil swelling closes the cracks. The % sand tends to increase with depth with values of 31.3%, 38.5%, 42.5%, and 42.2% for the respective depths of 0-0.3, 0.3-0.6, 0.6-0.9, and 0.9-1.2 m. The increase in the sand fraction with depth should be conducive to drainage.



12	13	36	37	60	61	84	85	108	109	132	133	156	157	180	181	204	205	228	229	252	253	276	277	300	301	324	325	348	349	372	373
11	14	35	38	59	62	83	86	107	110	131	134	155	158	179	182	203	206	227	230	251	254	275	278	299	302	323	326	347	350	371	374
10	15	34	39	58	63	82	87	106	111	130	135	154	159	178	183	202	207	226	231	250	255	274	279	298	303	322	327	346	351	370	375
9	16	33	40	57	64	81	88	105	112	129	136	153	160	177	184	201	208	225	232	249	256	273	280	297	304	321	328	345	352	369	376
8	17	32	41	56	65	80	89	104	113	128	137	152	161	176	185	200	209	224	233	248	257	272	281	296	305	320	329	344	353	368	377
7	18	31	42	55	66	79	90	103	114	127	138	151	162	175	186	199	210	223	234	247	258	271	282	295	306	319	330	343	354	367	378
6	19	30	43	54	67	78	91	102	115	126	139	150	163	174	187	198	211	222	235	246	259	270	283	294	307	318	331	342	355	366	379
5	20	29	44	53	68	77	92	101	116	125	140	149	164	173	188	197	212	221	236	245	260	269	284	293	308	317	332	341	356	365	380
4	21	28	45	52	69	76	93	100	117	124	141	148	165	172	189	196	213	220	237	244	261	268	285	292	309	316	333	340	357	364	381
3	22	27	46	51	70	75	94	99	118	123	142	147	166	171	190	195	214	219	238	243	262	267	286	291	310	315	334	339	358	363	382
2	23	26	47	50	71	74	95	98	119	122	143	146	167	170	191	194	215	218	239	242	263	266	287	290	311	314	335	338	359	362	383
1	24	25	48	49	72	73	96	97	120	121	144	145	168	169	192	193	216	217	240	241	264	265	288	289	312	313	336	337	360	361	384
Paddock 1				Paddock 2				Paddock 3				Paddock 4				Paddock 5				Paddock 6				Paddock 7				Paddock 8			

Figure 1 a. Tile drain and plot layout; b. Sample locations. ●Tile drain monitoring station.

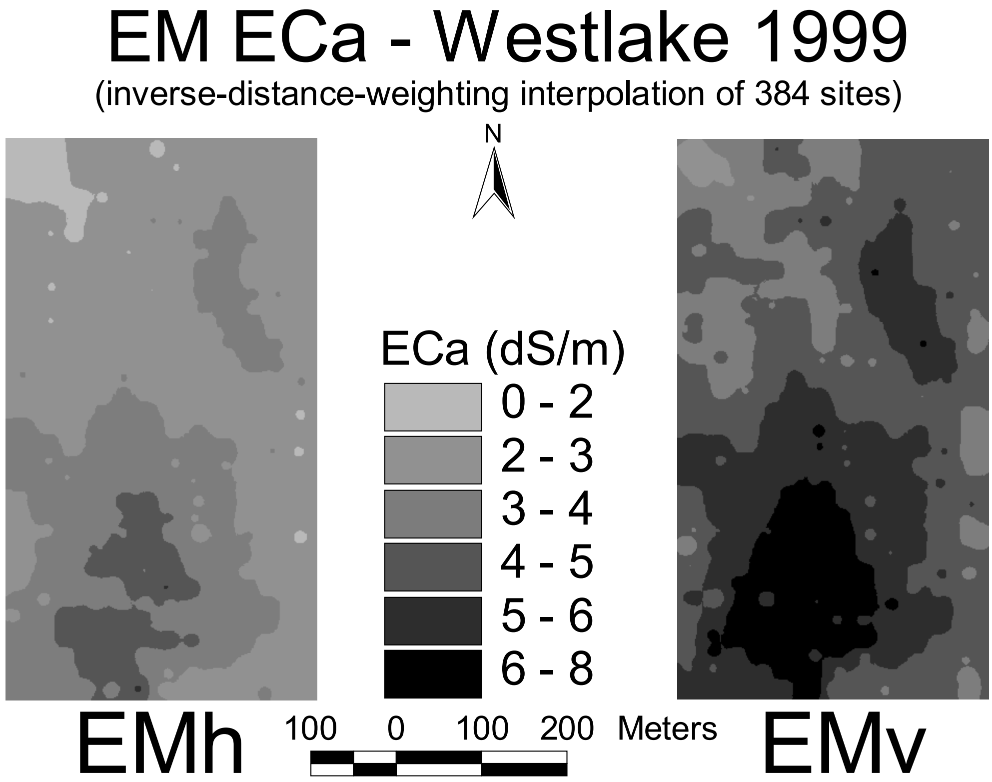


Figure 2 Maps of inverse-distance-weighting inperpolations of EMh and Emv. measurements.

Drainage water volume and initial water composition

Leaching is important to the sustainable reuse of drainage water. Some leaching appears to have occurred at the site historically, since salinity, Cl, and SAR increase with depth (Table 1). Both drainage volume and LF increased during the season (Table 2), particularly for Paddock 3. At the start of the irrigation season the water table was lower than the tile drains. It took several irrigations to establish a water table that was higher than the drains. Concurrent with the establishment of a higher water table, the EC of the drainage water increased, which is most evident in Paddocks 3 and 7; and LF also increased. The measured leaching fractions averaged 0.13 for Paddocks 6 and 7 during the last two irrigations that occurred during September. This number likely represents the leaching fraction that occurred during the establishment of the water table – the excess water passing through the rootzone was the only source of water to raise the water table because there were no irrigated fields within about 1 km of the field. Whether the method of measuring leaching fraction provides a valid number within the area served by the drain depends, in part, on the spatial and temporal variability in water infiltration and its redistribution within the root zone (Eching *et al*., 1994). It also depends on the assumption that drainage flows in the saturated zone are symmetric.

Table 1 Mean and range statistics four depth intervals between 0 and 1.2 m.

Label	Means				Coefficients of Variation			
	0.0-0.3 m	0.3 –0.6 m	0.6 -0.9 m	0.9 – 1.2 m	0.0-0.3 m	0.3 –0.6 m	0.6 - 0.9 m	0.9 – 1.2 m
PW (%)	20.8	26.3	27.0	30.6	18	15	20	24
Vol. H_2O (cm^3 cm^{-3})	0.30	0.40	0.40	0.43	20	12	12	11
ρ_b (g cm^{-3})	1.29	1.51	1.52	1.51	8	6	8	11
% Clay	35.9	30.4	26.2	23.3	19.1	16.0	25.9	26.9
EC_e (dSm^{-1})	13.0	20.2	22.5	25.2	58	26	29	31
pH_e	7.61	7.58	7.63	7.57	3	3	2	3
SP (%)	58.8	63.0	59.1	58.7	13	16	19	22
Cl, $mmol_cL^{-1}$	21.8	35.3	47.1	58.7	70	41	46	51
SAR	28.2	51.4	59.0	64.9	59	25	28	30
ESP (%)	28.4	41.6	47.5	51.8	52	23	28	39
B (mg L^{-1})	17.0	19.0	17.5	17.9	48	30	27	35
Se (μg L^{-1})	8.75	14.04	12.90	14.15	145	61	72	99
As (μg L^{-1})	8.19	8.83	12.94	4.42	151	150	181	183
Mo (μg L^{-1})	862	750	781	947	62	57	43	48
CEC ($mmol_c$ 100 g^{-1})	21.7	19.5	17.0	17.5	18	26	29	27
$CaCO_3$ (%)	1.08	1.04	1.14	1.27	75	103	110	115
Gypsum (%)	3.41	5.37	6.63	6.41	51	60	60	72

The year 2001 was the second year of developing the site and learning how to obtain and manage saline-sodic drainage water. Because of a drastic reduction in cropped area in 2001, saline-sodic water in the nearest evaporation pond (20 < EC (dS m^{-1}) <30) had to be pumped back into the drainage canal system and mixed with non-saline Kings River water (EC = 0.5 dSm^{-1}) to obtain the ECiw values given in Table 2. Consequently the salinity of the applied water was lower than the desired 5 – 9 dS m^{-1}, and varied from one irrigation to the next for each paddock.

Table 2 Irrigation and drainage water summary including leaching fraction (LF) for 2001. EC represents electrical conductivity, and the subscripts iw and dw represent irrigation water and drainage water, respectively.

Date	Irrigation	Drainage	EC iw	EC dw	LF
	mm		dSm^{-1}		
	Drain 6, Paddock 3				
18-Jul	158	0.01	0.4	8.7	< 0.001
2-Aug	99	0.96	3.1	14.4	0.010
24-Aug	142	0.61	3.4	11.5	0.004
14-Sep	130	2.06	1.7	16.2	0.016
28-Sep	77	4.88	3.4	31.3	0.063
	Drain 12, Paddock 6				
18-Jul	152	2.7	0.4	36.0	0.018
3-Aug	126	15.7	2.8	35.8	0.124
22-Aug	182	15.9	2.2	42.1	0.087
12-Sep	127	12.5	1.4	42.4	0.098
26-Sep	96	11.3	3.8	39.4	0.117
	Drain 14, Paddock 7				
19-Jul	177	1.5	0.6	22.6	0.008
2-Aug	132	13.7	4.0	31.6	0.104
21-Aug	182	23.8	4.1	37.1	0.131
12-Sep	120	15.3	1.3	35.6	0.127
26-Sep	96	16.0	3.3	37.2	0.167

Bermuda grass establishment and yield

Bermuda grass is a halophytic, C4 species with a large degree of salt tolerance. Grass yields declined with increasing soil salinity in the first 30 cm of soil (Figure 3). Above approximately 22 dSm^{-1}, little to no Bermuda grass was able to grow. This response matched estimates of salinity tolerance reported by Ayers and Westcott (1985). Consequently, in locations with the largest amounts of soil B and Mo, there was no forage to collect and none for cattle to graze.

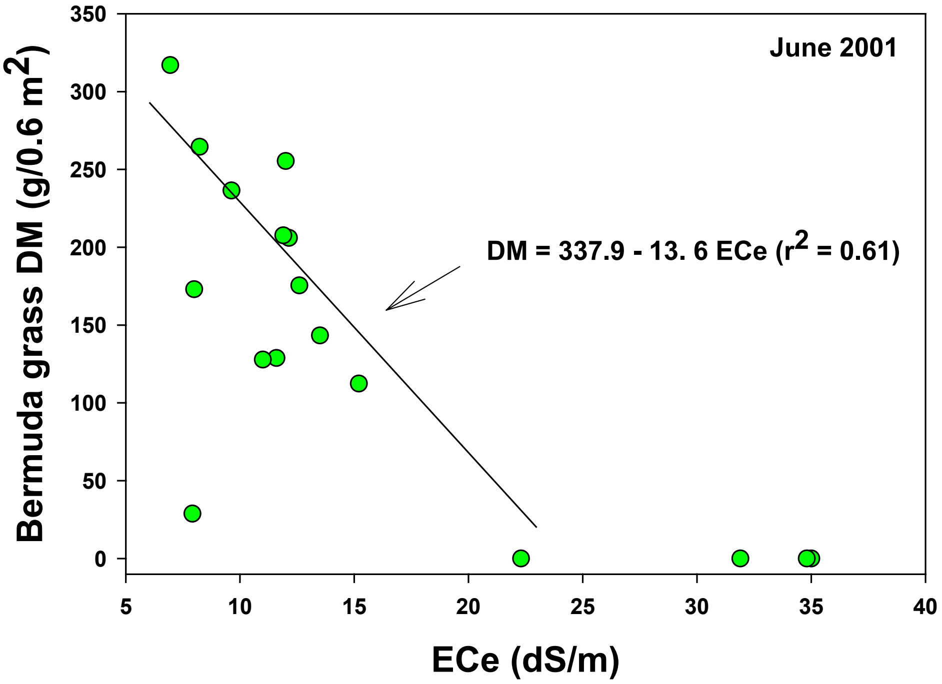


Figure 3 Forage yield in June 2001 in plots 1 and 4 compared to soil ECe.

Only limited information is available about the trace element uptake by Bermuda grass (Table 3), so comparisons cannot be made with literature values. Large amounts of soil Mo and B are found at this site. But forage Mo levels were not particularly high, likely because Bermuda grass did not grow in locations with the largest amount of soil Mo. Mo concentrations of 1 to 4 mg kg^{-1} are commonly observed values (Vlek and Lindsey, 1977; McBride *et al*., 2001; O'Connor *et al*., 2001). Mo may be toxic to cattle if consumed in large amounts, primarily by interfering with Cu metabolism (Suttle, 1991). The Mo concentrations reported are not excessive, especially in comparison to those reported as typical for legumes like alfalfa and clover, which is usually 2 to 4 times as enriched as grass species growing under similar conditions (O'Connor *et al*., 2001). The ratio of forage Cu to forage Mo (3.3:1) is above the ratio often cited for concern (2:1), but Suttle (1991) has proposed that the critical ratio declines as forage Mo increases. Cu levels of less than 5 mg kg^{-1} in the presence of soil Mo has been cited as of concern (Johansen, *et al*., 1997). Average Cu levels are greater than 8 mg kg^{-1} in these samples (Table 4). Crude protein levels, ADF, K, P, Ca, and Mg levels all are close to standard values used in ratio formulation tables, in the absence of specific forage analyses (National Research Council, 1989). Ash contents are higher on average than those considered typical. Few feeding studies and fewer actual grazing studies under the soil chemical conditions have been reported, so further work on livestock performance and health on these pastures will be of interest.

Large amounts of forage biomass accumulated on the site because grazing pressure in the first year was very slight. Cattle were used in 2001 only for livestock health determinations. Figure 4 reports standing forage biomass on a dry matter basis for sampling events throughout the 2001 growing season. On most of the site, Bermuda grass tolerated soil and irrigation water conditions and grew vigorously.

Table 3 Selected forage quality and mineral contents from Bermuda grass harvests in fall, 2000.

Label	**Mean**	**Minimum**	**Maximum**	**CV**
CP (%)*	16.0	9.31	22.1	18.3
Ash (%)	13.1	8.27	23.0	22.8
ADF (%)	29.4	22.1	36.4	10.9
P (%)	0.22	0.15	0.34	17.6
K (%)	1.98	1.07	3.41	23.4
S (mg kg^{-1})	7420	3780	9250	13.9
Ca (%)	0.49	0.35	0.77	20.9
Mg (%)	0.24	0.16	0.56	32.7
Na (mg kg^{-1})	7860	3600	23920	43.4
B (mg kg^{-1})	133	44	257	29.6
Cl (%)	0.89	0.36	3.31	52.6
Zn (mg kg^{-1})	35.5	17	58	1.23
Mn (mg kg^{-1})	80.8	46	132	22.9
Fe (mg kg^{-1})	667	175	4714	122.5
Cu (mg kg^{-1})	8.06	4.2	13.7	21.6
Mo (mg kg^{-1})	2.41	1.4	5.3	31.7
Se (µg kg^{-1})	88.5	16	328	67.8

Summary and Conclusion

Electronic methods used in this study provide a means of assessing soil quality at field scale. It facilitates reducing the number of soil samples needed to characterize the spatial variability of physical-chemical properties that impact crop productivity and the sustainability of irrigation (Aon *et al*., 2001) The initial assessment of soil quality and future spatio-temporal changes soil physico-chemical properties will used to evaluate the sustainability of drainage water reuse for forage production at the experimental site. in the WSJV. At the research site, due to their elevated levels, temporal changes in salinity, SAR, B, and Mo levels are long-term chemical concerns. Methods to characterize saturated hydraulic conductivities pose a problem. Field-measured saturated hydraulic values (Corwin, *et al*., submitted) were consistently higher (0.49 to 1.79 cm h^{-1}), than laboratory-measured values (0.0000846 to 0.0456 cm h^{-1}). The sustainability of drainage water reuse depends on maintaining a LF that prevents the accumulation of excessive salinity, B, and Mo to prevent the occurrence of toxic effects upon forage and grazing livestock, and yet low enough to meet the objective of minimizing drainage volumes and the dissolution of additional salts and minerals. Even though the soil at the research site has high SAR values with low measured saturated hydraulic conductivities, there are mitigating factors that make adequate leaching achievable: (1) the reused drainage water is high in salinity, (2) water flow through surface cracks is a common infiltration pathway of WSJV soils, (3) the presence of an efficient drainage system, and (4) a dense forage cover over most of the site. The establishment of a research site in the WSJV, coupled with forage and livestock management, provide an unusual opportunity to evaluate the sustainability of a drainage water reuse system at field scale, including its economic consequences for farms.

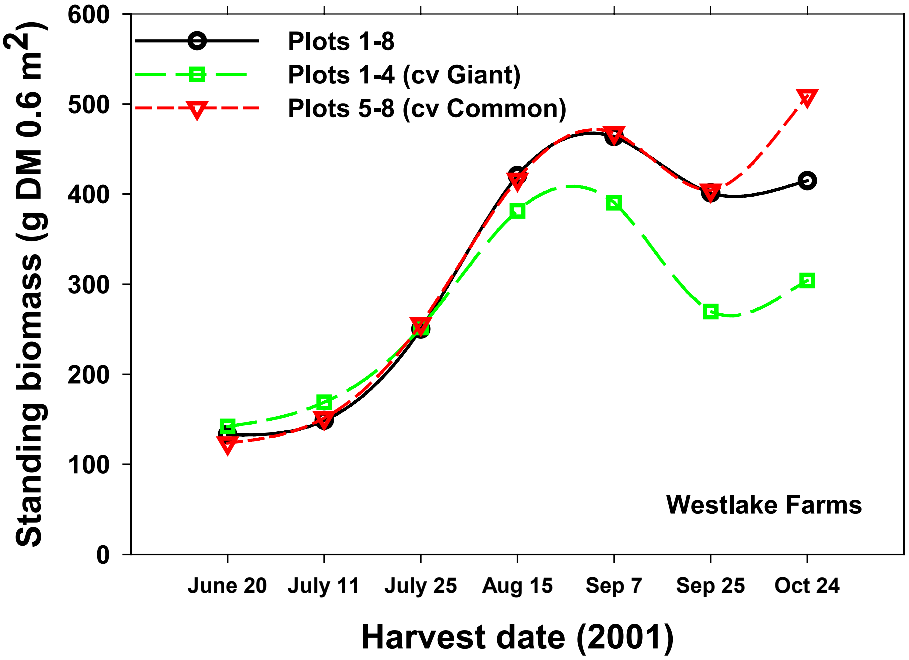


Figure 4 Standing forage biomass (g DM 6 m^{-2}) in 2001.

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