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Biomass yield and nutritional quality of forage species under long-term irrigation with saline-sodic drainage water: Field evaluation

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Abstract

On the Westside of California's San Joaquin Valley, the discharge of subsurface agricultural drainage water (DW) is subject to strict environmental regulations due to its high selenium (Se) content and potential risks to wildlife. Re-use of saline-sodic DW to irrigate salt-tolerant forage crops is attractive because it reduces the volume of DW requiring disposal and the land area affected by salinity, while producing forages to satisfy the large demand for animal feed resulting from rapid expansions in dairy and beef cattle operations in this area. The biomass production and nutritional quality of six forages ('Jose' tall wheatgrass, creeping wildrye, alkali sacaton, 'Alta' tall fescue, puccinellia and 'Salado/801S' alfalfa) were evaluated under DW irrigation on a commercial farm near Five Points in Fresno County, California. The forage fields were in their second to fifth year of DW application and most had soil salinities higher than 12 dS/m EC_e (electrical conductivity of the saturated soil paste extract). In addition to being very saline, the fields had high levels of boron (B), Se and sodicity [high sodium (Na) relative to calcium (Ca) and magnesium (Mg)]. 'Jose' tall wheatgrass and creeping wildrye had acceptable dry matter (DM) production (7.0 and 11.5 t/ha year) under highly saline

Abbreviations: CP, crude protein; DM, dry matter; $dNDF_{30}$, *in vitro* digestibility of NDF at 30 h; DW, drainage water; EC, electrical conductivity; IFDM, Integrated On-farm Drainage Management; ME, metabolizable energy; NDF, neutral detergent fibre; SAR, sodium adsorption ratio

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conditions of 19 and 13 dS/m EC_e, respectively. Alfalfa produced 16–20 t/ha year of DM under low salinity conditions of <7.0 dS/m EC_e. The forages had estimated metabolizable energy (ME) contents of 7.9–9.9 MJ/kg DM – with the exception of alkali sacaton (6.7 MJ/kg DM) – which would make them acceptable as feeds for beef cattle, sheep and some classes of dairy cattle. Selenium levels varied from 4.4 to 10.7 mg/kg DM in forages that had received 4–5 years of DW application. Forages at the high end of this range could cause Se toxicity in ruminants when used as a sole source of forage, but they could also be used as a Se supplement if fed at a rate of 20–40 g/kg in the Se-deficient areas found along the eastern SJV. Saline-sodic DW can be used as a water resource to produce forage suitable for many classes of ruminants, although drainage waters with high levels of Se may present both problems and opportunities.
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Keywords: Salt-tolerant forages; Drainage water re-use; Salinity; Selenium; Tall wheatgrass

1. Introduction

On the Westside of California's San Joaquin Valley, water-logging and the salinization of land are limitations to crop production. Growers in salt-affected lands are often limited to low value, salt-tolerant field crops rather than higher value vegetable crops. Subsurface drainage is an effective tool to prevent land salinization (Van Schilfgaarde, 1990) and sustain productive agriculture, but the management of saline drainage water (DW) has presented challenges to San Joaquin Valley agriculture (Oster and Grattan, 2002). A major factor complicating DW disposal in this area is its high content of Se. The Kesterson Reservoir (Merced, CA), which temporarily held agricultural DW in the early 1980's, was closed in 1986 due to Se bioaccumulation and the death of aquatic birds (Ohlendorf, 1989). Disposal of agricultural DW to surface water bodies was subsequently outlawed in this valley and so growers had to seek alternative, in-valley, strategies to manage DW. Several of these strategies aim to reduce DW volumes, thereby minimizing risks to wildlife. Re-use of DW for irrigation is an important strategy to achieve this goal (Shannon and Grieve, 2000; SJVDIP, 2000; Qadir and Oster, 2004).

Agricultural DW is often considered unsuitable for many crops, but manipulating irrigation and crop management can allow for the production of marketable crops. Production of salt-tolerant forages using DW is attractive due to the high demand for forages in the SJV and the relatively low level of crop management required. Several salt-tolerant forages were examined in a greenhouse sand tank study for their biomass productivity, salt-tolerance, mineral content and nutritional value for animal production (Robinson et al., 2004) and most had acceptable productivity and nutritional value when irrigated with the saline-sodic DW. However, salt-tolerance and productivity was different among species (Grattan et al., 2004a) and the accumulation of excessive levels of S, Mo and K was an animal health concern (Grattan et al., 2004b).

The objective of this study was to evaluate the performance of some of the more promising forage species from Robinson et al. (2004) and Grattan et al. (2004a,b), such as tall wheatgrass (*Thinopyrum ponticum* var. 'Jose') and alfalfa (*Medicago sativum* var. 'Salado'), under SJV field conditions. The value of the field study reported here is that the forages were grown under actual SJV soil conditions where cracking clay soils common to this area form tough surface crusts, and many years of irrigation with saline-sodic DW had considerably reduced soil permeability to water and oxygen. These additional stresses can affect forage performance and their overall suitability in salt-affected environments (Rogers et al., 2005). To our knowledge, there are relatively few studies (Kaffka et al., 2004) on the productivity and nutritional value of forages grown under field conditions with multiple years of DW irrigation, which influences in particular, the degree of trace mineral accumulation in the forage and its potential toxicity to the animals that consume it.

2. Materials and methods

2.1. Experimental site

Red Rock Ranch is a commercial farm located in the Westlands Water District (WWD), 10 km southwest of Five Points in Fresno County (CA, USA). The ranch is located on the alluvial fan and flood plain of Cantua Creek which creates a shallow water table. The 260 ha Integrated On-farm Drainage Management (IFDM) demonstration project that has operated on the ranch since 1994 includes four stages (*i.e.*, land areas) where the more salt-sensitive crops are grown under irrigation with freshwater and salt-tolerant forages and halophytes are grown under irrigation with DW. In this sequential re-use system, DW is collected under the area planted with salt-sensitive crops (stage 1) and then sequentially re-used on progressively more salt-tolerant plants (stages 2–4). The final effluent from the system is conducted to a terminal solar evaporator (Fig. 1). More detailed information on this IFDM system is available in Jacobsen and Basinal (2004).

Six forages were grown in eight fields (two fields for tall wheatgrass and creeping wildrye and one each for the other forages) at RRR (Table 1 and Fig. 1). Fields varied in size from 0.4 to 16.2 ha. Two 3 m × 3 m sampling plots were established in each of the eight fields for productivity and forage quality determination.

All forages were established by the grower with freshwater [*i.e.*, electrical conductivity (EC) <1.5 dS/m] for at least 6 months. With the exception of the alfalfa and CWR 1, the forages were in their fourth and fifth year of DW irrigation during most of the sampling period. The alfalfa field was irrigated entirely with freshwater, except for a small portion (ALF/DW) which was irrigated with blended DW by furrow irrigation beginning in the spring of 2003 (Table 1). Management of the forage fields (*i.e.*, salinity of the irrigation water, method of application and irrigation frequency) was at the discretion of the grower.

2.2. Sampling and laboratory analysis

2.2.1. Soil and water

The soil at RRR was mapped as a saline-sodic Ciervo clay in the Western Fresno County soil survey (Cervinka et al., 1999; USDA-NRCS, 2004), but textural determination of samples collected from the forage plots classified the soils as clay loams. Two sampling plots were established in each forage field and the locations were geo-referenced using a Global Positioning System (eTrex Venture, GARMIN Corp., Taipei County, Taiwan). Soil samples

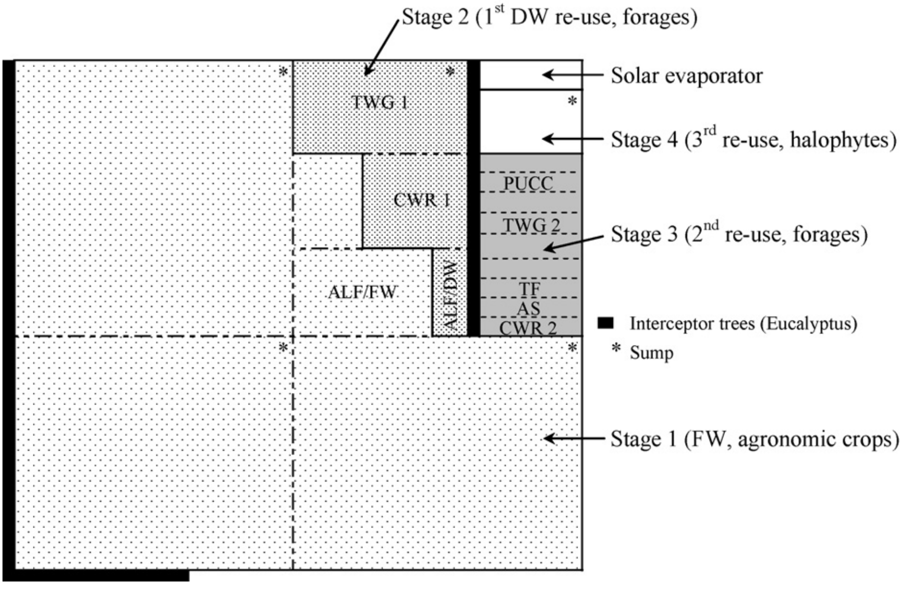

Fig. 1. Map of Red Rock Ranch DW re-use demonstration project: stage 1 (FW irrigated) = 188 ha; stage 2 (first re-use) = 52 ha; stage 3 (second re-use) = 5.2 ha; stage 4 (third re-use) = 2 ha; and solar evaporator = 0.8 ha. Each stage is delineated by a solid line and individual forage fields by dashed lines. TWG, tall wheatgrass; CWR, creeping wildrye; PUCC, puccinellia; TF, tall fescue; AS, alkali sacaton; ALF/FW, alfalfa irrigated with freshwater; ALF/DW, alfalfa irrigated with drainage water.

Table 1
Forages species, field size, planting date, and years of irrigation with saline-sodic DW at Red Rock Ranch

Forages	Species	Area (ha)	Planting[a]	DW irrigation[b]
Tall wheatgrass (TWG 1)	*Thinopyrum ponticum* (Host) Beauv. var. 'Jose'	16.2	1998	1997
Tall wheatgrass (TWG 2)	syn. *Agropyron elongatum*	0.4	1998	2000
Creeping wildrye[c] (CWR 1)	*Leymus triticoides* (Buckl.) Pilger var. 'Rio'	8.1	2001[d]	2003
Creeping wildrye (CWR 2)	syn. *Elymus triticoides* Buckl.	0.4	1998[d]	2000
Puccinellia (PUCC)	*Puccinellia ciliata*	0.4	1998	2000
Tall fescue (TF)	*Festuca arundinacea* var. 'Alta'	0.4	1998[d]	2000
Alkali sacaton (AS)	*Sporobolus airoides* Torr. var.'Solado'	0.4	1998[d]	2000
Alfalfa DW (ALF/DW)	*Medicago sativum* L. var. 'Salado' and '801S'	0.6	2001	2003
Alfalfa FW (ALF/FW)[e]	*Medicago sativum* L. var. 'Salado' and '801S'	15.6	2001	–

Sampling was conducted from fall 2002 to fall 2004.

[a] Forages were planted in the fall.

[b] Year when DW irrigation began.

[c] Also called as beardless wildrye.

[d] Transplants used for planting. All other fields were seeded.

[e] Irrigated only with freshwater.

were collected in the fall of each year at depths of 0–15 and 15–30 cm in 2002, and then at depths of 0–30 and 30–60 cm thereafter, including the fall of 2004. Soil samples were air-dried and ground to pass a 1 mm screen prior to chemical analysis.

Saturated soil pastes were prepared with deionized water and allowed to stand overnight prior to vacuum filtration. Soil salinity (EC_e) was measured on the paste extract using an EC meter (YSI Model 3100 Conductivity system, Yellow Springs, OH, USA). Concentrations of Ca, Mg and Na were also measured on the paste extract using a GBC 902 AES atomic absorption and emission spectrophotometer (GBC Scientific Equipment Pty Ltd., Melbourne, NSW, Australia), in order to calculate the sodium adsorption ratio (SAR), an indicator of soil sodicity. Chloride and SO_4 were measured on the saturated paste extracts according to EPA method 300.0 (EPA, 1993) with a Dionex DX-500 ion chromatography (IC; Sunnyvale, CA, USA). Boron was determined on the saturated paste extract using EPA method 200.7 (EPA, 1994) with inductively coupled plasma atomic emission spectrometry (ICP-AES). A sub-sample of soil was oven dried at 55 °C for 48 h to measure total Se and NO_3-N using a flow injection analyzer method (Knepel, 2003). Organic forms of Se were digested using nitric, perchloric and sulfuric acid and the resulting inorganic forms were quantified using vapor generation inductively coupled plasma emission spectrometer (Thermo Iris ICP, Thermo Electron Corporation, Waltham, MA, USA) (Tracy and Moeller, 1990).

Samples of irrigation water were collected and Cl, SO_4 and B concentrations were measured using the methods described above. Nitrate was measured according to EPA method 300.0 and total phosphate by EPA method 365.1 (EPA, 1993). Na, K, Ca and Mg were measured by EPA method 200.7, and Se by EPA method 200.8 (EPA, 1994).

2.2.2. Forage sampling

Forage tissue was sampled for 2 years starting in September 2002. Productivity was measured using a rotational cutting system in which the entire forage plot was initially cut to a 12–15 cm height above the soil surface, and then cuts were taken in 1 m^2 sub-plots when the stand reached 30 and 45 cm. When the forage in the plot reached its final height prior to heading (or 10% flowering for alfalfa), the entire plot was trimmed to 15 cm. This method allowed measurement of standing biomass, rather than re-growth after the last cut. The mean dry matter (DM) for the two plots was summed for the period of September 2002–2003 (first year) and September 2003–2004 (second year). The cumulative DM yield for the plot (kg/m^2) was then converted to tonnes of DM per hectare (t/ha).

Harvested forage tissue was rinsed in deionized water to remove surface salts and dust and then dried in a forced air oven at 60 °C for 48 h. Dried tissues were ground to pass through a 1 mm screen in a Thomas–Wiley laboratory Mill (Model 4, Thomas Scientific, Swedesboro, NJ, USA) for subsequent tissue analysis.

2.2.3. Forage tissue analysis

Metabolizable energy (ME) was determined using 24 h *in vitro* gas values combined with CP, and fat contents (Menke and Steingass, 1988). Procedures of the Association of Official Analytical Chemists (AOAC, 2000) were used for the determination of crude fat (AOAC ID 920.39) and ash (AOAC ID 942.05). Crude protein (CP) was calculated from N that was determined by sample combustion at high temperature in pure oxygen and measured by thermal conductivity detection (AOAC, 2000; ID 990.03). Neutral detergent fibre (NDF) was determined by using the ANKOM fiber technique as described in Robinson et al. (1999). *In vitro* digestibility of NDF ($dNDF_{30}$) at 30 h were determined by incubating the samples in multi-layer polyester cloth bags (Robinson et al., 1999) without sodium sulfite and α-amylase and expressed inclusive of residual ash. The $dNDF_{30}$ was only measured during the second year.

Forage Na and K contents were measured using atomic absorption spectrometry and Ca, Mg, P, S, B and Mo were measured by ICP-AES (Meyer and Keliher, 1992; Sah and Miller, 1992). Se was measured by the same method described for soil analysis. Chloride was measured using acetic acid extraction and electrometric titration as described in Johnson and Ulrich (1959). Nitrate–N was measured using acetic acid extraction and reduction to nitrite via a copper cadmium column (Carlson et al., 1990; Wendt, 1999). All forage harvests during the first year were analyzed. In the second year, tissue analysis was conducted for April, July and October samples to compare seasonal differences in forage quality and ion composition.

3. Results

3.1. Irrigation water and soil conditions in DW irrigated fields

The salinities of the DW used to irrigate stage 2 fields (*i.e.*, TWG 1 and CWR 1) were 8.6–10.5 dS/m, the B concentrations were 12.8–19.4 mg/L and the Se concentrations were 0.29–0.59 mg/L (Table 2). The TWG 1 field in stage 2 had very high soil salinity (EC_e = 19.1 dS/m, 0–60 cm depth), sodicity (SAR = 38.0) and B concentration (25.1 mg/L), whereas the CWR 1 field had a soil salinity of 13.3 dS/m EC_e, SAR of 29.4 and 18.7 mg/L of soluble soil B (Table 3).

In stage 3 where the TWG 2, CWR 2, PUCC, TF and AS fields were located, the irrigation water salinity was 9.8 dS/m and the B and Se concentrations were 15.9 and 0.55 mg/L, respectively (Table 2). Soil salinity (EC_e), SAR, and total Se in soil were similar in the CWR 2, TF and AS fields; but in the PUCC and TWG 2 fields, EC_e was higher (15.0 and 17.6 dS/m, respectively) and B concentrations were about 23 mg/L (Table 3).

In the alfalfa field, the freshwater–water irrigated portion (ALF/FW) had relatively low soil salinity (4.7 dS/m), SAR (12.2) and soil B (3.6 mg/L). The portion irrigated with DW (ALF/DW) of 6.7 dS/m had an average EC_e of 6.9 dS/m, SAR of 17.5, and soluble soil B was 7.1 mg/L.

3.2. Forage productivity

Tall wheatgrass (TWG) growing in the highly saline fields (EC_e = 17.6–19.1 dS/m) produced from 5.9 to 8.3 t/ha of DM (Fig. 2). The very low DM yield in TWG 2 in the first year was likely due to inadequate irrigation. Creeping wildrye (CWR) growing in fields with soil salinities of 12.9–13.3 dS/m EC_e produced 10.0–13.8 t/ha. Under freshwater irrigation, ALF/FW produced 17.1–21.0 t/ha, as compared to 16.6 t/ha under DW irrigation (ALF/DW). Puccinellia (PUCC) is a cool season grass that only grows from late fall to spring. In spite of its short growing season, the single harvest in the spring yielded 5.6 t/ha in a field having a soil salinity of 15 dS/m EC_e.

Table 2
Salinity (EC_w), sodium adsorption ratio (SAR), and ion composition of the irrigation water applied to forage fields in 2004

	n[a]	EC_w (dS/m)	Cl (mequiv./L)	SO_4 (mequiv./L)	Na (mequiv./L)	Ca (mequiv./L)	Mg (mequiv./L)	SAR	B (mg/L)	Se (mg/L)	NO_3-N (mg/L)	K (mg/L)
Stage 1												
ALF/FW	5 (1)	1.10	1.7	0.4	1.8	0.8	1.80	2.0	<0.1	<0.01	0.2	2.4
Stage 2												
ALF/DW[b]	2 (1)	6.72	22.6	48.1	52.0	17.8	6.16	15.0	10.8	0.22	23.8	11.3
TWG 1[c]	6 (1)	10.48	36.7	37.7	77.0	35.2	14.56	15.4	19.4	0.59	88.4	0.8
CWR 1[d]	3 (1)	8.58	45.2	88.4	100.6	26.3	11.76	22.9	12.8	0.29	44.3	7.9
Stage 3												
TWG 2, CWR 2, PUCC, TF and AS	8 (6)	9.78	30.1	72.9	66.8	25.8	9.08	16.0	15.9	0.55	95.5	4.3

All fields were irrigated with saline DW with the exception of alfalfa which was irrigated with blended drainage water. ALF/FW, alfalfa with freshwater; ALF/DW, alfalfa irrigated with drainage water; TWG, tall wheatgrass; CWR, creeping wildrye; PUCC, puccinellia; TF, tall fescue; AS, alkali sacaton.

[a] Number of EC_w samples. The *n* for SAR and ion composition are indicated in parenthesis.

[b] DW was blended with freshwater.

[c] Sample taken in 2002.

[d] Non-saline water used for irrigation during the first year after transplanting, and then saline DW applied in 2003 and 2004.

Table 3
Soil salinity (EC_e), sodium adsorption ratio (SAR), pH, sulfate, boron and selenium concentrations in forage fields during 2002–2004

Forage field[a]	EC_e[b] (dS/m)	SAR	pH_p[c]	SO_4 (mg/L)	B (mg/L)	Total Se (mg/kg)
TWG 1	19.1 ± 0.9	38.0 ± 2.0	8.05 ± 0.1	8.559 ± 228	25.1 ± 1.6	3.28 ± 0.3
TWG 2	17.6 ± 0.4	35.3 ± 1.5	8.00 ± 0.1	7.966 ± 174	23.0 ± 1.2	3.26 ± 0.2
CWR 1	13.3 ± 0.6	29.4 ± 1.2	7.72 ± 0.1	5.426 ± 222	18.7 ± 1.3	1.87 ± 0.1
CWR 2	12.9 ± 0.6	28.1 ± 1.4	7.82 ± 0.1	6.270 ± 272	18.7 ± 1.0	3.97 ± 0.2
PUCC	15.0 ± 1.0	29.9 ± 1.7	7.99 ± 0.1	6.960 ± 278	23.2 ± 1.2	3.21 ± 0.3
TF	12.1 ± 0.4	27.3 ± 1.2	7.98 ± 0.1	6.032 ± 172	16.8 ± 0.7	3.22 ± 0.5
AS	12.4 ± 0.5	26.7 ± 1.0	7.87 ± <0.1	5.855 ± 174	15.8 ± 0.8	2.89 ± 0.4
ALF/DW	6.9 ± 0.7	17.5 ± 1.2	7.75 ± 0.1	2.899 ± 392	7.1 ± 1.0	1.34 ± 0.1
ALF/FW	4.7 ± 0.7	12.2 ± 1.9	7.67 ± <0.1	1.925 ± 365	3.6 ± 0.6	1.35 ± 0.1

Data are means ± S.E. for 0–60 cm soil depth with the exception of Se and SO_4 which are for the 0–30 cm depth. $n = 18$ for all fields, except for EC_e and pH_p are $n = 20$.
[a] TWG, tall wheatgrass; CWR, creeping wildrye; PUCC, puccinellia; TF, tall fescue; AS, alkali sacaton; ALF/DW, alfalfa with drainage water; ALF/FW, alfalfa with freshwater.
[b] Electrical conductivity of the saturated soil paste extract.
[c] pH of the saturated soil paste.

3.3. Forage quality (metabolizable energy, protein and fibre content)

Alfalfa had high ME (9.6 and 9.9 MJ/kg DM, respectively) for the freshwater and DW irrigated portions of the field (Table 4), and AS had low ME (6.7 MJ/kg DM). Among the DW irrigated grasses, TWG, PUCC and TF had ME values of 9.2–9.6 MJ/kg DM, close to that of alfalfa.

The CP of the grass forages ranged from 113 to 190 g/kg DM, whereas alfalfa had a CP of 237 and 248 g/kg DM for ALF/DW and ALF/FW, respectively. The NDF was about 540–650 g/kg DM for all of the DW irrigated grasses. The exception was AS, which had an

Table 4
Metabolizable energy (ME), crude protein (CP), neutral detergent fibre (NDF), digestibility of NDF ($dNDF_{30}$) and ash content of forages

Forage field[a]	n	ME (MJ/kg DM)	CP (g/kg DM)	NDF (g/kg DM)	$dNDF_{30}$[b] (g/kg DM)	Ash (g/kg DM)
TWG 1	16	9.3 ± 0.3	156 ± 10	565 ± 27	540 ± 32	97 ± 4
TWG 2	10	9.2 ± 0.3	113 ± 7	621 ± 19	602 ± 33	80 ± 5
CWR 1	16	8.2 ± 0.3	164 ± 13	609 ± 30	459 ± 18	87 ± 3
CWR 2	15	7.9 ± 0.2	139 ± 9	651 ± 13	429 ± 26	81 ± 3
PUCC	6	9.6 ± 0.4	177 ± 17	604 ± 15	747 ± 2	88 ± 4
TF	12	9.3 ± 0.3	190 ± 11	544 ± 14	618 ± 13	115 ± 6
AS	14	6.7 ± 0.2	121 ± 4	722 ± 9	402 ± 24	93 ± 5
ALF/DW	24	9.6 ± 0.1	237 ± 12	375 ± 19	432 ± 14	99 ± 3
ALF/FW	24	9.9 ± 0.1	248 ± 11	348 ± 23	438 ± 13	103 ± 2

Data are means ± S.E. from fall 2002 to 2004, with the exception of $dNDF_{30}$ which are means for fall 2003–2004.
[a] Forages are TWG, tall wheatgrass; CWR, creeping wildrye; PUCC, puccinellia; TF, tall fescue; AS, alkali sacaton; ALF/DW, alfalfa irrigated with drainage water; ALF/FW, alfalfa irrigated with freshwater.
[b] Digestible NDF at 30 h incubation.

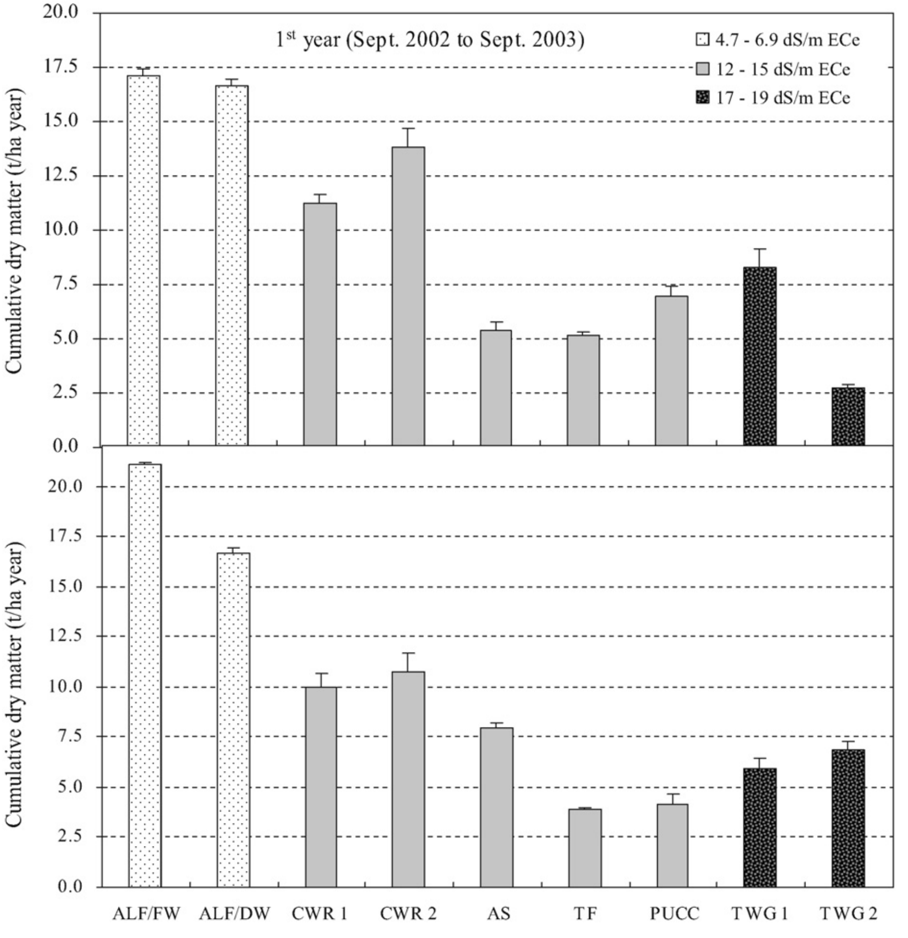

Fig. 2. Cumulative dry matter production (means ± S.E.M.) of the forages from 2002 to 2004. Forages include 'Salado/801S' alfalfa irrigated with freshwater (ALF/FW) and drainage water (ALF/DW), creeping wildrye (CWR), alkali sacaton (AS), tall fescue (TF), puccinellia (PUCC) and tall wheatgrass (TWG). Shading in the bars indicates the salinity level of the fields where forages were growing.

NDF of 722 g/kg DM, which is above acceptable levels in most ruminant feeding options. AS also had low digestibility of NDF, at 402 g/kg DM. Forage ash levels ranged from 80 to 115 g/kg DM.

3.4. Minerals

The Se concentration in all DW irrigated forages was above 2 mg/kg, the maximum tolerable concentration for most ruminants (Minson, 1990; NRC, 1996). The only exceptions were CWR 1, which had been irrigated with DW for less than 2 years and ALF/DW which had been irrigated with blended DW for only 1 year (Table 5). Forages that had been irrigated

Table 5
Mineral content (means ± S.E.) of forages from fall 2002 to 2004

Forage field[a]	DW irrigation[b] (years)	*n*	EC_e (dS/m)	NO_3-N (mg/kg DM)	Se (mg/kg DM)	Mo (mg/kg DM)	B (mg/kg DM)	S (g/kg DM)	Na (g/kg DM)	K (g/kg DM)	Ca (g/kg DM)	Mg (g/kg DM)	P (g/kg DM)
TWG 1	5	16	19.1 ± 0.9	131.6 ± 23.8	6.12 ± 0.3	1.54 ± 0.3	5161 ± 92	3.6 ± 0.3	8.9 ± 1.6	13.8 ± 0.5	2.2 ± 0.2	1.3 ± 0.1	1.1 ± 0.0
TWG 2	5	10	17.6 ± 0.4	59.8 ± 23.3	7.38 ± 0.7	1.87 ± 0.2	349 ± 61	3.5 ± 0.5	6.4 ± 1.1	16.2 ± 1.2	2.3 ± 0.3	1.1 ± 0.2	1.6 ± 0.1
CWR 1	2	16	13.3 ± 0.6	134.0 ± 35.7	2.98 ± 0.5	2.2 ± 0.2	318 ± 89	2.2 ± 0.1	1.2 ± 0.3	24.5 ± 1.4	3.0 ± 0.3	1.1 ± 0.1	1.7 ± 0.1
CWR 2	5	15	12.9 ± 0.6	99.8 ± 24.2	10.72 ± 1.2	1.41 ± 0.2	322 ± 63	4.1 ± 0.4	2.5 ± 0.5	19.1 ± 1.7	3.2 ± 0.3	1.4 ± 0.1	1.2 ± 0.1
PUCC	5	6	15.0 ± 1.0	86.7 ± 29.5	4.37 ± 1.8	0.75 ± 0.3	92 ± 84	2.9 ± 0.5	6.0 ± 0.8	24.2 ± 2.1	2.7 ± 0.4	1.1 ± 0.1	2.0 ± 0.2
TF	5	12	12.1 ± 0.4	184.2 ± 36.2	7.41 ± 1.2	3.80 ± 1.1	990 ± 165	5.7 ± 0.6	11.5 ± 1.7	17.6 ± 0.9	4.1 ± 0.4	1.9 ± 0.1	1.6 ± 0.1
AS	5	14	12.4 ± 0.5	63.3 ± 17.9	6.88 ± 0.8	1.31 ± 0.1	344 ± 27	5.9 ± 0.0	1.3 ± 0.4	17.9 ± 0.0	5.9 ± 0.7	1.9 ± 0.1	1.0 ± 0.0
ALF/DW	1	24	6.9 ± 0.7	213.4 ± 58.2	1.45 ± 0.1	4.35 ± 0.2	146 ± 12	3.7 ± 0.2	5.3 ± 0.6	22.6 ± 1.0	15.0 ± 0.5	2.4 ± 0.1	2.7 ± 0.1
ALF/FW	0	24	4.7 ± 0.7	96.7 ± 58.8	0.80 ± 0.1	4.80 ± 0.3	102 ± 8	3.4 ± 0.1	3.2 ± 0.4	24.2 ± 1.3	15.5 ± 0.5	2.4 ± 0.1	2.6 ± 0.1
RC[c]				–	0.10	–	–	1.5	0.6–0.8	6.0	–	1.0	–
MTC[d]				1000.0	2.00	5.00	–	4.0	–	30.0	–	4.0	–

Soil salinity (EC_e) is also shown to indicate the large differences in salinity among the forage fields.

[a] Forages are TWG, tall wheatgrass; CWR, creeping wildrye; PUCC, puccinellia; TF, tall fescue; AS, alkali sacaton; ALF/DW, alfalfa irrigated with drainage water; ALF/FW, alfalfa irrigated with freshwater.

[b] Years of DW irrigation at the end of second year of sampling.

[c] RC = required concentration based on non-lactating beef cattle (NRC, 1996).

[d] MTC = maximum tolerable concentration based on non-lactating beef cattle (NRC, 1996).

with DW for 5 years had Se concentrations of 4–10 mg/kg, and CWR 2 had 10.7 mg/kg, which is in the 'potentially toxic' range (Aitken, 2001). Se concentrations of the freshwater irrigated alfalfa were 0.8 mg/kg, which is a safe level for feeding to most ruminants (NRC, 1996).

Sulfur concentrations in all DW irrigated forages, except CWR 1, ranged from 3 to 6 g/kg DM which are close to, or above, the maximum tolerable concentrations of 4 g/kg DM established for most ruminants (NRC, 1996, 2001). The B concentrations were also high (92–990 mg/kg DM) in most of the DW irrigated forages. In spite of very high levels of NO_3 in the applied DW, forage NO_3 concentrations remained well below 1000 mg/kg NO_3-N, the safe limit for ruminant feeding under most conditions (NRC, 2001).

4. Discussion

Soil chemical conditions (*e.g.*, soil salinity, B, and sodicity) varied among the fields because of pre-existing spatial variability and management differences, such as the number of years of DW irrigation and the salinity of the applied DW. However, all fields were typical of DW irrigated fields in the San Joaquin Valley. The alfalfa fields ($EC_e < 7$ dS/m) represent low salinity conditions in a DW re-use system such as IFDM, and the CWR fields ($EC_e = 13$ dS/m) represent intermediate salinity conditions. The TWG fields with an average rootzone salinity of 19 dS/m EC_e are among the most saline fields found under DW irrigation in this valley (Table 5).

Although the salinity and B concentrations of the DW were typical of those found in the SJV, Se concentrations were very high due to local geologic conditions (Fujii and Deverel, 1989). Soil Se concentrations are usually much lower at other sites in the SJV where DW re-use takes place (Cervinka et al., 1999). Consequently, in the soils irrigated with DW at Red Rock Ranch, Se concentrations in the forage were also very high (Table 5).

The main factor affecting Se uptake by plants is total available Se in the soil, in particular selenate, but factors such as soil pH, texture and SO_4 concentrations can also influence Se uptake (Mikkelsen et al., 1989). Soil pH varied little in these soils, but SO_4 concentrations were very high due to the sodium sulfate-dominated salinity of the area. Although SO_4 can reduce Se uptake by plants due to anion competition for root absorption sites (Grieve et al., 2001), Se accumulation was very high in our forages, and was related to the very high Se concentrations in the soil and DW used for irrigation. For example, creeping wildrye (CWR) growing in field 2 where total Se in soil was 4 mg/kg after 5 years of DW irrigation, accumulated 10.7 mg/kg DM in forage tissue. In contrast, the same forage growing in a field lower in Se (1.9 mg/kg total Se with 2 years of DW irrigation) accumulated only 3 mg/kg DM of Se in its tissue. In the earlier sand tank study (Grattan et al., 2004b), Se concentrations remained below 2 mg/kg DM in all of the forages, even though they were irrigated with simulated DW containing 0.5 mg/L Se. These lower forage Se values were presumably due to the shorter period (1 year) of DW irrigation, and the frequently irrigated sand medium, which does not concentrate elements as do fine-textured field soils.

4.1. Forage yield

'Jose' tall wheatgrass (TWG) grown at Bushland (Texas) produced 11.7–13.5 t/ha year with weekly irrigation with freshwater and about 100 kg/ha/year of applied nitrogen (Lauriault et al., 2002). In our study TWG produced 7 t/ha year, on the average, and considering the harsh growing conditions (*i.e.* high soil salinity and sodicity), this productivity was judged to be very good. No N fertilizer was applied to our forage fields because the DW used for irrigation contained as much as 95.5 mg/L NO_3-N. TWG was also one of the most salt-tolerant and highest DM producers in the prior sand tank study (Grattan et al., 2004a).

Creeping wildrye (CWR) consistently produced more than 10 t/ha in both fields 1 and 2 with average rootzone salinities of 13 dS/m EC_e. Although this salinity level is much lower than that of the TWG fields, it is well above that of soils classified as non-saline which generally have an $EC_e < 4$ dS/m (SSSA, 1997). In comparison, tall fescue (TF) growing in soils with similar salinities as the CWR field produced only 4–5 t/ha year, suggesting that this forage is only suitable for less saline soil conditions. Puccinellia (PUCC) grew only during the cooler November–April months, but it produced 5.6 t/ha year at a soil salinity of 15 dS/m EC_e. In the SJV, most rainfall occurs from December to March and this non-saline water source likely contributed to the rapid growth of this forage, which could provide a reliable source of hay in early spring when the supply of warm season forage is often limited.

'Salado/801S' alfalfa had a high DM production (>16 t/ha year) under non-saline to moderately low salinity conditions (6.9 dS/m EC_e). Bañuelos et al. (2003) reported slightly lower DM production (13.8 t/ha year) for 'Salado' alfalfa grown under irrigation with Westside San Joaquin Valley drainage water and at a similar soil salinity of 5.2–6.4 dS/m EC_e. Alfalfa also produced high DM yield under low salinity ($\sim$7 dS/m EC_e) in the prior sand tank study (Grattan et al., 2004a). In this study, the alfalfa irrigated with DW had stunted growth and quickly developed 'burn' (necrosis) on the margin of the leaves, probably due to the high B concentration (10.8 mg/L) in the blended DW. These B toxicity symptoms worsened in the summer as tissue B concentrations increased (data not shown), presumably due to higher temperatures and higher evapotranspiration.

4.2. Forage quality

All forages, except for alkali sacaton (AS), had ME above 7.9 MJ/kg DM. In general, an ME value below 7 MJ/kg DM is considered to be unacceptable for beef cattle and goats (NRC, 1981, 1996). Forages with an ME between 7 and 9 MJ/kg DM are suitable for low production or maintenance level beef cattle, and those with an ME higher than 10 MJ/kg DM are acceptable for dairy cattle and rapidly growing calves. Under irrigation with saline DW, the forage quality of TWG, CWR, PUCC and TF would classify as acceptable for beef cattle feed, whereas the alfalfa ME would be marginally acceptable for dairy cattle.

In the prior sand tank study (Robinson et al., 2004), AS had medium to high forage quality (*i.e.*, ME of 7.8–9.4 MJ/kg DM). In contrast, our AS had low ME (6.7 MJ/kg DM) and low forage DM production (6.7 t/ha year). The high NDF in this forage reduces potential

DM intake by ruminants, thereby making AS unsuitable for beef cattle and goats, even at maintenance intake.

4.3. Selenium

When fed to high production ruminants, forages usually comprise 300–500 g/kg of the ration. Thus, the mineral levels of the forages (*e.g.*, Ca, Mg, P) are not critical because these nutrients can be supplied by the other feeds. However, forages should not contain concentrations of toxic ions, especially Se, above the maximum tolerable concentration which for Se is considered to be 2 mg/kg (NRC, 1996). Se toxicity in livestock usually occurs when they are fed Se accumulator plants (*e.g.*, *Astragalus* spp.) which contain exceptionally high tissue concentrations of Se; whereas toxicity from feeding non-accumulator plants rarely occurs (James et al., 1989). Generally, ruminants avoid eating high Se forages and a high S content such as in our DW irrigated forages, is likely to reduce Se absorption by the animals (Underwood and Suttle, 1999). Nevertheless, chronic Se toxicity, known as alkali disease or blind staggers, has developed when forages containing as little as 5–10 mg/kg of Se were fed to cattle (James et al., 1989; NRC, 1996).

If these DW irrigated forages were the only source of the feed, such as under grazing conditions, the risk of Se toxicity would increase. However, if animals consumed these forages containing 6–7 mg/kg Se at 400 g/kg of their total ration, their Se intake would still be in the safe zone of less than 3 mg/kg. In the San Joaquin Valley, cattle are commonly moved from the Coastal Range and Sierra Nevada Mountains in May or June to graze for 5–6 months on the valley floor. Ruminants can tolerate high Se feeds for short periods of time, but with these DW irrigated forages the potential for Se toxicity should considered when they are grazed, or fed at high levels in the ration.

Se accumulation in forages will be a concern for saline DW re-use systems on the Westside San Joaquin Valley. However, in many parts of the world, Se deficiency in forages is more common than is Se toxicity (MacPherson, 2000), and this includes the eastside San Joaquin Valley where forages are often Se-deficient (Suarez et al., 2003). Rather than considering Se-enriched forages as a problem, these forages could be identified and processed as Se supplements. Studies on utilization of high Se, salt-tolerant forages for this purpose would be useful. For most ruminants, the dietary Se requirement is only 0.1–0.3 mg/kg (Minson, 1990; NRC, 1996), therefore forages with 6–7 mg/kg could be used as a Se supplement at only 20–40 g/kg of the total diet to provide the required amount of Se for most ruminants, including beef and dairy cattle.

4.4. Sulfur

The S content of these DW irrigated forages was slightly above the maximum tolerable concentration of 4 g/kg DM (NRC, 1996); although if these forages comprised less than 400 g/kg of the total diet, the S content would be well below this level. S toxicity should be monitored, however, if cattle are grazed. High levels of S in forages can lead to increased sulfide production by ruminal microorganisms (Kandylis, 1984), which increases the incidence of cerebrocortical necrosis, also known as polioencephalomalacia (PEM; Gould et al., 1991; Gould, 1998). While supplementation to prevent S toxicity is possible, sulfide toxicity should be monitored because high sulfide in the rumen can also reduce Cu availability due to the formation of thiomolybdates, a non-absorbable form of Cu (Suttle, 1991).

4.5. Molybdenum

Alfalfa and most other legumes accumulate more Mo than do grasses (Minson, 1990; NRC, 1996). Molybdenum concentrations were very high in our alfalfa tissue (Table 5), as expected, but they remained below the maximum tolerable concentration of 5 mg/kg DM (NRC, 1996). More importantly, the combination of high Mo and S can cause Cu deficiency. Sulfur and Mo concentrations in these DW irrigated alfalfa were about 3.5 g/kg and 4.5 mg/kg, respectively. Spears (2003) reported that Cu availability in sheep was not affected when S and Mo concentrations in the forage were 3 g/kg and 4 mg/kg, respectively, but Cu availability was reduced 40–70% when S and Mo were 4 g/kg and 4.5 mg/kg, respectively. However, Cu deficiency can take months to develop because of a large potential reserve of Cu in the liver (Minson, 1990).

5. Conclusions

Achieving acceptable forage productivity is a challenge when using highly saline-sodic DW with high levels of B. However, under the field conditions of this experiment, acceptable levels of DM production were obtained from both tall wheatgrass and creeping wildrye. 'Salado/801S' alfalfa is a very attractive forage for dairy producers due to its high ME, but under IFDM management where DW is being used for irrigation, it can only be recommended for fields where the soil salinity is below 5–6 dS/m EC_e. Alkali sacaton had the lowest forage quality and is unsuitable for cattle, even at maintenance levels. Puccinellia had a very short growing season, but it could fit into an IFDM system because of its high biomass productivity in the late winter and early spring.

Se concentrations were very high in most of forages and above the recommended levels for most classes of cattle—especially in the forages that had been irrigated for 5 years with the high Se DW. Creeping wildrye accumulated the highest levels of Se among the forages, but species variability of Se accumulation should be examined under more controlled conditions. Further research is also necessary to determine acceptable levels of Se in forages, in terms of concentration and tolerable exposure for ruminants.

Although trace element accumulation is probably unavoidable for forages grown in DW re-use systems such as IFDM, adverse effects on animals may be avoided if concentrations are measured in the forages, and periodically in the blood of the animals, and rations or grazing patterns are adjusted accordingly. Analysis of the irrigation water and soil where the forages are grown can also reveal potential nutritional risks for animals, even before the forages are harvested.

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