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RESPONSE OF TALL FESCUE TO IRRIGATION WATER SALINITY, LEACHING FRACTION, AND IRRIGATION FREQUENCY

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ABSTRACT

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A long-term study in the rhizotron at the U.S. Salinity Laboratory established the yield and evapotranspiration of tall fescue as a function of irrigation water salinity, leaching fraction, and irrigation frequency. As the salt concentration of the irrigation water increased or leaching fraction decreased, dry matter production was reduced significantly. Differences in production because of irrigation frequency, however, were insignificant. With low stress (high leaching, L = 0.27, and low salinity water, S = 1 dS/m) annual dry matter yields were 2.0 kg/m^2, compared to annual yields of 1.4 kg/m^2 with high stress (low leaching, L = 0.09, and high salinity water, S = 4 dS/m).

Annual evapotranspiration dropped from 1860 mm for low stress treatments to 1170 mm for high stress. Soil evaporation was negligible for the mature grass stand. In concurrence with several models, relative dry matter production was proportional to relative water use.

The salt tolerance of treatments dominated by osmotic potential was in agreement with that published for tall fescue. As matric potential decreased among treatments yields fell significantly below that predicted by the salt tolerance model.

INTRODUCTION

Crop response to changes in soil matric and osmotic potentials which occur over time and with soil depth is a continuing issue in water mangement. The issue remains unresolved because of the complexity of interacting variables with these two components of total soil water potential. In typical studies, either matric or osmotic potential is varied while the other is held constant or changes are judged to be insignificant. Studies on crop response to osmotic potential are usually conducted at high soil water contents to minimize the effect of matric potential. Likewise, salinity is generally insignificant in studies on soil matric potential. In irrigated agriculture, however, both components of total soil water potential are present. Irrigation water, unless it is uncontaminated snowmelt or rainfall, contains signifi-

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cant concentrations of dissolved salts which, without proper management, can lead to crop loss from excessively low osmotic potentials. Likewise, if irrigations or precipitation are untimely or insufficient, diminished matric potentials can reduce yields. In the field both potential components work in unison; as evapotranspiration occurs the soil dries and salts are concentrated in the remaining soil water.

Altering the irrigation frequency is one possible technique for controlling both matric and osmotic potentials. When saline water is used for irrigation, it is generally recommended that the interval between irrigations be shortened. Results from experiments on medium-textured soils testing this recommendation, however, are contradictory. Ayoub (1977) and Bernstein and Francois (1975) found yields decreased as irrigation frequency increased, although the results of Bernstein and Francois were influenced by foliar adsorption from sprinkling. Irrigation frequency was reported to have no effect on yield of bean (Wadleigh and Ayers, 1945) and alfalfa (Bernstein and Francois, 1973) under saline conditions, while Ayers et al. (1943) and Wadleigh et al. (1946) found that irrigation frequency must be increased to minimize salt damage. Recently, Shalhevet et al. (1983) found no reduction in the yield of eggplant when the irrigation interval was increased from 2 to 12 days with saline as well as nonsaline irrigation waters; extending the interval to 16 days reduced yield significantly with both water qualities.

The primary objective of this study was to evaluate the influence of the salt concentration of irrigation water and the frequency of water application on fescue yield at three leaching fractions. Thus, this study differed significantly from those where soil water is depleted during the growing season and leaching curtailed (e.g., Hanks et al., 1978; Stewart et al., 1975). Where salinity is prominent, deficit irrigation can lead to soil salination and yield loss. With the prerequisite for leaching, irrigation amounts were dictated by the leaching fraction but irrigation frequency treatments were selected to create significant differences in soil matric potential.

EXPERIMENTAL PROCEDURE

A rhizotron, consisting of 24 fully enclosed soil plots, was designed and constructed during 1974. Each plot was 3.0 m by 3.0 m by 1.5 m deep. The plots were arranged in four rows of six plots each with two 3-m-wide roofed service areas providing horizontal accessibility to the soil profile on one side of every plot. This horizontal access was utilized when installing sensors, taking soil samples, or studying roots. A 4-m-wide roofed basement extended across one end of the four rows of plots for pumps, laboratory sinks, irrigation meters and controls, and storage. The plot floors were 10-cm-thick concrete and three of the plot walls were of grouted 15-cm-thick concrete blocks that were asphalt waterproofed. The fourth wall, adjacent to the service area, was constructed in four sections of 19-mm thick plywood with steel I-beam supports. Starting at the floor of the plot, each section consisted of a 15-cm-high panel and two panels each 70 cm high.

Drainage water was extracted from each plot through ten 3-m-long drain lines consisting of nine porous ceramic tubes connected in series with flexible joints. Each ceramic tube was 30 cm long and 10 mm in diameter. The drain lines were placed 12 cm above the concrete floor. Plastic tubes connected to the drain lines extended through sealed holes in the bottom panel. The drain lines for each plot were manifolded together and effluent was extracted under about 300 mm of Hg suction. Any gravity drainage was collected from a centrally-located floor drain covered with fine gravel.

The plots were filled in successive layers in 1975 with Pachappa fine sandy loam topsoil (coarse, loamy, mixed, thermic, Mollic Haploxeralf). Before each layer was added to the plots, the bulk soil was spread, tilled several times, and remixed repeatedly. Initially, a 15-cm depth of soil was placed in each plot and settled by saturating with water. After the soil dried, the porous drain lines were installed and tested for leaks before a 30-cm depth of soil was added. After another saturation and drying cycle, the drains were tested again and failures repaired. Soil was then added to increase the soil depth in each plot to 1.2 m. Following a saturation and drying cycle two sets of tensiometers and three sets of salinity sensors were installed at four depths (25, 45, 75, and 120 cm) along a diagonal line across each plot. The tensiometer leads were constructed of coaxial tubing so that both the tensiometer and salinity sensor leads could be buried below the final soil surface and installed through the wooden wall of each plot into the service area. The coaxial tubing permitted the tensiometers to be read and flushed from within the service area (Huber and Dirksen, 1978). Following sensor installation, an additional 25-cm depth of soil was added to each plot. The irrigation system was then installed after another saturation and drying cycle.

The irrigation system consisted of 18 lines of bi-wall drip irrigation tubing that had water-emitting holes spaced every 30 cm. The irrigation laterals were spaced 15 cm apart, and the emitting holes were turned upward to minimize plugging. A flow control valve for each plot limited irrigation flow to 63 ml/s. The irrigation system was tested before it was covered with 5 cm of soil to bring the total soil depth in each plot to 1.5 m. In 1979, new drip tubing was installed on the soil surface in every plot.

In April 1978, two neutron access tubes were installed in each plot to monitor soil water content with a neutron probe. The soil removed as the access tubes were installed was used to calibrate the neutron probe and to measure soil bulk density. Bulk density averaged 1.57 Mg/m^3 for the entire profile with a standard error of $\pm$ 0.01 Mg/m^3. The largest variation in bulk density by 15-cm depth increments was 0.05 Mg/m^3. This value compares with a bulk density of 1.46 Mg/m^3 for the natural undisturbed soil profile using soil cores (Wesseling, 1974). Furthermore, a moisture retention curve developed from tensiometer and neutron probe readings in this experiment agreed with the curve reported by Wesseling (1974).

Tall fescue (*Festuca elatior arundinacea*) was plated during September 1976 in each plot and the area around the rhizotron. Before the experimental treatments were initiated, the plots were irrigated with nonsaline water (electrical conductivity of 0.6 dS/m) at frequent intervals to maintain soil matric potential near —15 J/kg. Yields from the first cutting on 23 November 1976 were not recorded. However, before the treatments were initiated on 16 May 1977, 13 cuttings were taken to establish yield uniformity among the plots. The grass was cut to a height of 6 cm after it reached approximately 18 cm. During the experiment, the fescue was harvested 18 times each year. Harvests occurred every 16 days, on the average, from March until November but only three harvests were made during the winter.

The experiment was a three-factor, three-level design of the cube plus cuboctahedron plus four center points type (DeBaun, 1959). The three factors were irrigation frequency (F), leaching fraction (L), and salt content of the irrigation water (S). The treatment which consisted of the middle level of each variable was replicated four times to secure the experimental error term for the analysis of variance. The remaining 20 treatments covered the complete range of the factors and were not replicated. The reader is referred to Table II for a listing of all treatments. For brevity, treatments are identified by the code (F, L, S).

The irrigation waters consisted of various concentrations of NaCl, $CaCl_2$, $MgCl_2$ and $NaNO_3$ added to tap water (Table I). The electrical conductivities of the three irrigation waters were approximately 1, 2.5, and 4 dS/m and are so designated in the treatment code. All three irrigation waters had a sodium adsorption ratio of about 2.5. The $NaNO_3$ supplied the equivalent of about 200 kg/ha of nitrogen annually. Rainfall was excluded by covering the plots with reinforced plastic sheeting. Two storage tanks, buried adjacent to the plots and having a capacity of 16 m^3 each, provided two irrigation water salinities. The third water quality was an equal mix of the two stored waters.

The irrigation frequency treatments were pulse irrigations daily to prevent any significant depletion of the soil water beyond that required to maintain the desired leaching fraction, designated as (0) in the treatment code; irrigations when approximately 1/3 of the available soil water had been lost from the root zone (0—1 m depth) for the nonsaline treatments, designated as (1); and irrigations when 2/3 of the available soil water had been depleted, (2). The irrigation system applied water at the rate of 2.5 mm/h for all treatments; thus, on the average, 0—5 h were required to apply daily irrigations, 1—3 days were required to apply the total irrigation for the 1/3 depletion treatments, and 4—6 days were required for the 2/3 depletion treatments. The number and duration of the pulses for the daily irrigation treatments varied depending on evapotranspiration. For the 1/3 depletion treatments, irrigations were as frequent as every 10—14 days and as infrequent as monthly; seventeen irrigations were applied annually on the average. Eleven irrigations were applied annually for the 2/3 depletion treatments; as often as every 20—25 days and as infrequent as bi-monthly.

The amount of water applied each irrigation was based upon several indicators. First, the amount of water lost from the soil profile between irrigations was estimated based upon measurements of soil water content and soil matric potential. Second, evapotranspiration of the unstressed treatments was estimated from measurements of pan evaporation. Finally, the actual amount applied was adjusted based upon the difference between the actual and the desired L for each treatment; if L was low extra water was applied. The three leaching fraction treatments were 0.09, 0.18, and 0.27 and are so noted in the treatment code.

Irrigation volumes were measured with two water meters, placed in series, to secure accurate and fail-safe readings for each plot. Drainage volumes for each plot were collected in several glass bottles, 20 l volume each, connected in series. On the average, irrigation and drainage volumes were measured twice weekly; soil matric potential, soil salinity, and soil water content were measured weekly.

A salt balance was calculated for each treatment. With the exception of a few treatments where the salinity of the soil water was higher at the beginning than at the end of the time period, the only salt input was the irrigation water. The change in salt storage in the soil water was computed from the differences in initial and final salt sensor readings. Salt output from drainage was taken as the product of the volume-weighted salt concentration of the drainage water and the drainage volume. The amount of salts precipitated in the soil profile were determined from the drainage water composition model of Oster and Rhoades (1975) assuming the CO_2 concentration in the soils to be 0.03% and using the ion activity products reported by Suarez (1977). The amount of salts precipitated is not a great deal different among treatments because only Cl salts were added to the tap water to increase the salinity of the irrigation waters (see Table I). The mass of salt removed in the grass clippings was assumed to be equal to the amount of plant ash. Ash, the plant mass remaining after incineration at 550°C for 2 h, averaged 0.1 kg per kg of dry matter (dried for several days at 60°C). Nitrate was added at the rate 1.6 mol/m^3 of irrigation water and only 0.1—0.3 mol/m^3 remained in the drainage; the difference was assumed to be lost by denitrification or removal by the plant.

At the conclusion of the experiment the influence of the three factors on root density was evaluated by taking two soil cores horizontally through the wooden wall of eight treatments. Each soil core had a volume of 900 cm^3 and was taken at a horizontal distance of 30—60 cm into the soil monolith near the center of each plot. The mass of dry roots per unit volume was determined by washing the roots from the soil and allowing them to float off into a collection box. The treatments sampled were: (0, 0.27, 1),

TABLE I

Electrical conductivity, sodium-adsorption-ratio, and concentration of major constituents of the three irrigation waters

Irrigation water salinity treatment (dS/m)	Average electrical conductivity (dS/m)	Average salt concentration (g/m^3)	Sodium[a] adsorption ratio ($(mol/m^3)^{0.5}$)	Ion concentrations (mol/m^3)							
				Ca	Mg	Na	K	CO_3 /HCO_3	Cl	SO_4	NO_3
1.0	0.95	675	2.5	1.9	0.8	4.0	0.1	3.5	2.9	0.7	1.6
2.5	2.69	1500	2.4	5.8	3.1	7.0	0.3	2.7	19.4	0.7	1.6
4.0	4.17	2320	2.5	9.8	5.2	9.8	0.5	2.4	34.9	0.7	1.6

[a]Sodium adsorption ratio = $Na/\sqrt{(Ca+Mg)}$ with concentrations in mol/m^3.

(0, 0.27, 4), (0, 0.09, 1), (0, 0.09, 4), (2, 0.27, 1), (2, 0.27, 4), (2, 0.09, 1), and (2, 0.09, 4). This selection permitted comparisons between four treatments receiving daily irrigations and four receiving irrigations after a 2/3 depletion of soil water. Likewise, comparisons could be made between 1 and 4 dS/m irrigation waters and 0.09 and 0.27 leaching fractions. Samples were taken at eight depths (10, 20, 30, 40, 50, 60, 80, and 120 cm) at two locations in each treatment.

RESULTS

The experimental results are divided into three categories: water balance, soil salinity, and plant response. In addition to measurements of the components for a water balance, time-integrated values of volumetric water content and soil matric potential through the soil profile are presented. For soil salinity, closure on salt balance is given along with the distribution of soil salinity through the soil profile. The response of fescue to the various treatments is presented in terms of dry matter production and root distribution.

Water balance

Irrigation (I) and drainage (D) quantities, reported as the average depth of water per unit of soil surface area, are summarized in Table II. Annual depths of irrigation ranged from a high of 2630 mm for the control treatment (0, 0.27, 1) to 1280 mm for treatment (1, 0.09, 4). Drainage depths varied in accordance with leaching fraction, averaging 135 mm for 9% leaching, 330 mm for 18% leaching, and 620 mm for 27%. Evapotranspiration (E_t), computed as the difference between irrigation and drainage with a correction for any change in soil storage, ranged from 1860 mm for the control treatment to 1170 mm for treatment (1, 0.09, 4). Annual pan evaporation (E_p) measured at the site averaged 1825 mm. Thus, the average ratio of E_t/E_p was 1.01 for the three irrigation frequencies at an L of 0.27 with water having a salinity of 1 dS/m. The ratio remained near 1 throughout the year. The average leaching fraction ($L = D/I$) achieved over the 3-year treatment period for each plot is also given in Table II. Treatments designed for a leaching fraction of 0.09 averaged 0.094, those for 0.18 averaged 0.176, and those for 0.27 averaged 0.263.

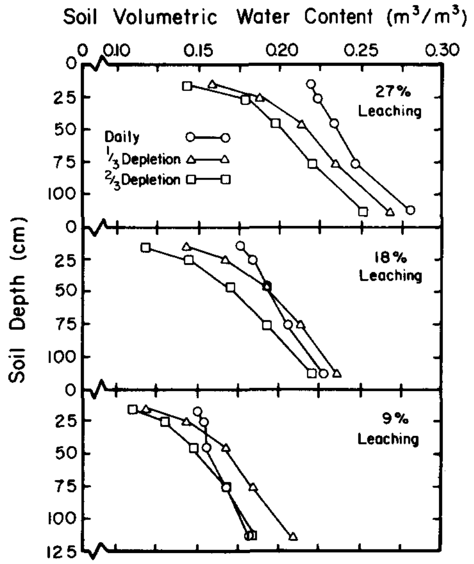
The volumetric water content (θ) averaged for the soil profile and integrated over time ($\bar{\theta}$), is given in Fig. 1 as a function of leaching fraction and irrigation frequency. The value of $\bar{\theta}$ increased with increasing leaching fraction and increasing soil depth. For this soil the average value of $\bar{\theta}$ at a depth of 120 cm corresponding to leaching fractions of 0.09, 0.18, and 0.27 were 0.19, 0.23, and 0.27 m^3/m^3, respectively. The maximum θ measured one day after an irrigation was 0.32 m^3/m^3. Undisturbed soil cores reached a θ of 0.45 m^3/m^3 at saturation in the laboratory (Wesseling, 1974).

TABLE II

Average annual depths of irrigation, I (mm), drainage, D (mm), and evapotranspiration, E_t (mm) for each treatment during the period May 1978 to May 1981 rounded to the nearest 5-mm; leaching fraction ($L = D/I$) is also given

Treatment		Irrigation depth (mm)	Drainage depth (mm)	Change in soil storage (mm)	Evapotranspiration (mm)	Leaching fraction
Leaching fraction	Irrigation salinity (dS/m)					
Daily irrigations (0)						
0.09	1	1715	120	+20	1575	0.070
	2.5	1565	115	+15	1435	0.073
	4	1370	165	−10	1215	0.120
0.18	1	1950	375	+30	1545	0.192
	4	1815	340	+15	1460	0.187
0.27	1	2630	740	+30	1860	0.281
	2.5	2370	660	+15	1695	0.278
	4	2205	710	0	1495	0.322
Irrigations after 1/3 *depletion* (1)						
0.09	1	1610	110	−10	1510	0.068
	4	1280	115	−5	1170	0.090
0.18	2.5	1715	335	−15	1395	0.195
	2.5	1910	270	−10	1650	0.141
	2.5	1835	325	−10	1520	0.177
	2.5	2000	290	0	1710	0.145
0.27	1	2410	665	0	1745	0.276
	4	2290	645	−10	1655	0.282
Irrigations after 2/3 *depletion* (2)						
0.09	1	1590	165	+15	1410	0.104
	2.5	1370	145	+10	1215	0.106
	4	1410	130	+10	1270	0.092
0.18	1	1970	370	−15	1615	0.188
	4	1755	320	+10	1425	0.182
0.27	1	2515	575	+5	1935	0.229
	2.5	2175	450	+10	1715	0.207
	4	2160	500	+10	1650	0.231

As an example of the changes in θ during several irrigation cycles, the average water content of the entire soil profile (θ_p) is given in Fig. 2 for the last 3 months of the experiment. Treatments for each irrigation frequency studied with the highest (0.09, 4) and the lowest stress (0.27, 1) are illustrated. For daily irrigations θ_p increased with time as evapotranspiration increased to maintain a constant L. The values of θ_p for the highest and lowest stress treatments that were irrigated daily averaged 0.18 and 0.27 m^3/m^3, respectively. Four irrigations for the 1/3 depletion treatments occurred over the time period depicted in Fig. 2. For the low stress treatment θ_p increased from 0.23 to 0.30 m^3/m^3 during an irrigation compared to an increase from 0.15 to 0.23 m^3/m^3 for the high stress treatment. The



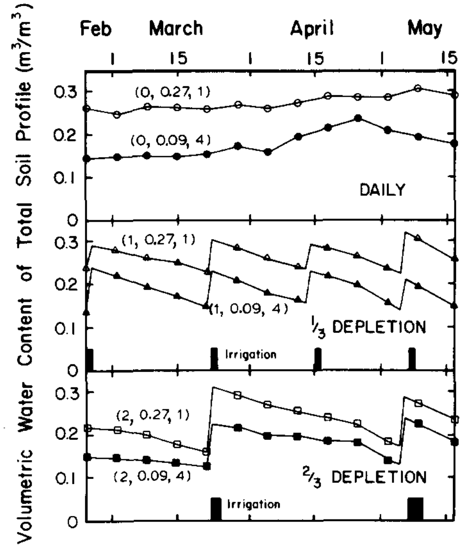


Fig. 1. Time-integrated values of volumetric water content through the soil profile as a function of leaching fraction and irrigation frequency.

Fig. 2. Volumetric water content of the total soil profile for the two extreme treatments for each irrigation frequency studied during the last 3 months of the fescue experiment.

change in θ_p during an irrigation for the two irrigations after 2/3 depletion was significantly higher than for the 1/3 depletion treatments: 0.16 to 0.30 m^3/m^3 for low stress and 0.12 to 0.23 m^3/m^3 for high stress. The time-integrated values of θ_p over the 3-month period were 0.27, 0.26, and 0.23 m^3/m^3 as irrigation interval increased for the low stress treatments and 0.18, 0.19, and 0.17 m^3/m^3 for the high stress treatments, respectively.

Soil matric potential (ψ_m) measured at the 45-cm soil depth with tensiometers during the last 3 months of the experiment is given in Fig. 3. Matric potential at the 25-cm depth dropped below the tensiometer range frequently for both the 1/3 and 2/3 depletion treatments. Matric potential at depths of 75 and 120 cm were less responsive to irrigations than those at a depth of 45 cm, as expected. The trends in ψ_m parallel those of θ_p in Fig. 2. For the high stress treatment, ψ_m dropped below —70 J/kg prior to each irrigation for the 2/3 depletion treatment; in contrast, ψ_m dropped to about —50 J/kg before each irrigation for the 1/3 depletion treatment.

Soil salinity

The time-integrated soil salinity profiles, measured with salt sensors, are illustrated in Fig. 4. The values at the soil surface are the salinity values of the irrigation waters. The average salinities of the drainage waters are given for the 150-cm depth. Because irrigation frequency did not influence yield

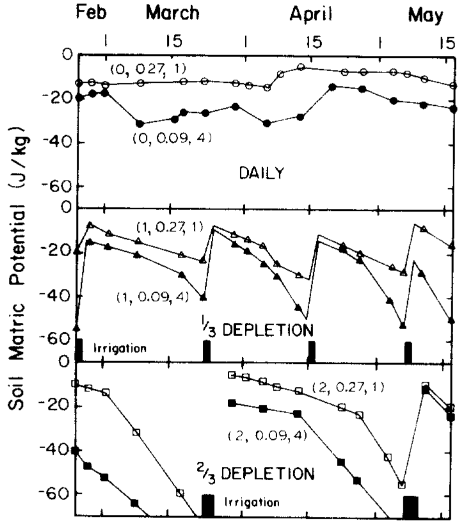
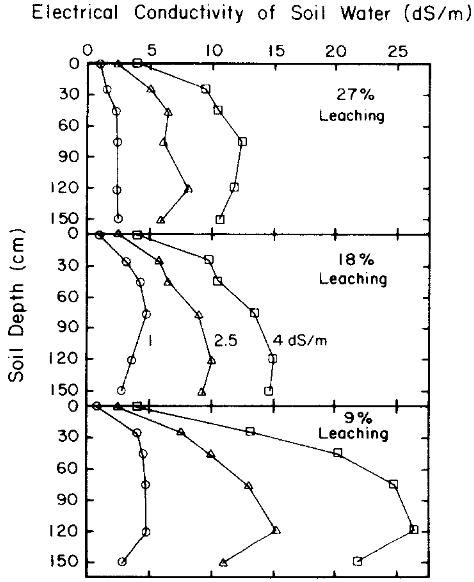


Fig. 3. Soil matric potential at the 45-cm depth for the two extreme treatments for each irrigation frequency studied during the last 3 months of the fescue experiment.



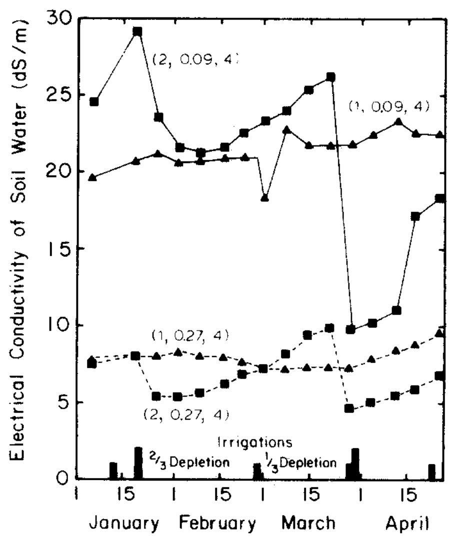


Fig. 4. Time-integrated values of the electrical conductivity of soil water through the soil profile as a function of leaching fraction and irrigation water salinity. The electrical conductivity of the irrigation water is shown at the soil surface and the electrical conductivity of the drainage water is given at the 150-cm soil depth.

Fig. 5. Time course of soil salinity at a depth of 45-cm as a function of irrigation frequency (1/3 depletion, 1; and 2/3 depletion, 2) and leaching fraction (0.09 and 0.27) when the irrigation water has an electrical conductivity of 4 dS/m for several irrigation cycles.

significantly, salinity profiles for the irrigation frequency treatments were combined. Thus, the salinity profile given for 27% leaching with an irrigation water salinity of 4 dS/m is the average for treatments (0, 0.27, 4), (1, 0.27, 4), and (2, 0.27, 4). The salinity profiles are as expected. The salinity of the drainage waters, weighted by drainage volume for May 1978 to May 1981 are consistently less than soil salinity values at a depth of 120 cm. This difference is caused by the time lag in reaching representative salinity values with increasing soil depth in the profile (Gish and Jury, 1982) and the possibility of some water moving in large pores through the soil profile.

In parallel with the soil matric potential examples, Fig. 5 illustrates the change in soil salinity during several irrigation cycles at the 45-cm depth. A void in salt sensor readings precluded reporting data for exactly the same time period as in Fig. 3. For daily irrigations, salinity values remained relatively constant at 17.1 dS/m for treatment (0, 0.09, 4) and 10.3 dS/m for treatment (0, 0.27, 4). Salt sensor readings at the 45-cm depth responded to irrigations after 2/3 depletion but not to irrigations after 1/3 depletion. The difference in response to the two irrigations following 2/3 depletion is caused by a much larger irrigation in March compared to January to account for increased E_t.

The components of the salt balance for each treatment are given in Table III for the time period of May 1978 to May 1981. The major salt input for this balance is, of course, from the irrigation water. In a few treatments, the salt content of the soil profile was higher at the beginning than at the end and this loss of salt from soil storage (a positive value in the soil storage column in Table III) is a salt input. All of the remaining components listed in Table III are salt outputs and have negative signs. In most treatments salt storage continued to increase with time, particularly near the bottom of the soil profile. The largest increases in soil water salinity occurred in the 9% leaching treatments, as expected. The amount of salt precipitation was about the same for all treatments, ranging from 6.7 to 12.3 kg. The amount of salts precipitating was not a function of irrigation water salinity because only Cl salts were added to increase salt concentration above that of the tap water.

The accumulated error in measuring the salt balance for each treatment is given in the last column of Table III. The error ranged from −6 to +9% with the average being 1.5%. The largest sources of error in the balance calculations were the sporadic measurements of the salt concentration of the drainage waters in 1978 and 1979 and the reliance on salt sensor readings at the 120-cm soil depth to indicate changes in soil salinity in the lower 30% of the soil profile.

Plant response

Yield. The relative yields (Y_r) for each treatment throughout the experiment are summarized in Table IV. The absolute dry matter yields are also

TABLE III

Salt balance for each treatment from May 1978 to May 1981

Treatment		Salt in irrigation water (kg)	Change[a] in soil water salinity (kg)	Salt output				Measurement error[b] (%)
Leaching fraction	Irrigation salinity (dS/m)			Drainage (kg)	Salt precipitation (kg)	Plant uptake (kg)	Denitrification (kg)	
Daily irrigations (0)								
0.09	1	+ 31.3	− 9.7	− 5.8	− 6.7	−4.3	−4.6	+1
	2.5	+ 63.4	−19.4	−21.1	−10.8	−4.6	−4.1	+5
	4	+ 85.8	− 9.0	−62.7	− 9.4	−4.0	−3.6	−3
0.18	1	+ 35.5	− 4.2	−16.2	− 7.0	−5.1	−5.2	−6
	4	+113.7	−17.6	−82.2	−10.8	−4.5	−4.7	−5
0.27	1	+ 47.9	+ 0.6	−28.1	− 7.3	−5.6	−6.9	+1
	2.5	+ 96.0	− 7.5	−58.2	−11.6	−5.1	−6.2	+8
	4	+138.1	− 1.2	−121.5	−11.3	−4.8	−5.8	−5
Irrigations after 1/3 depletion (1)								
0.09	1	+ 29.3	− 6.6	− 5.7	− 6.8	−4.3	−4.3	+5
	4	+ 80.2	−17.0	−42.5	− 8.7	−3.4	−3.4	+6
0.18	2.5	+ 69.5	− 1.1	−53.8	− 9.6	−4.5	−4.5	−6
	2.5	+ 77.4	− 3.2	−46.7	−12.3	−4.3	−5.1	+7
	2.5	+ 74.3	− 5.2	−47.2	−10.7	−4.6	−4.8	+2
	2.5	+ 81.0	− 3.1	−47.6	−12.6	−4.7	−5.3	+9
0.27	1	+ 43.9	+ 0.3	−27.6	− 6.7	−5.5	−6.3	−4
	4	+143.4	+ 1.2	−109.2	−11.8	−5.1	−6.0	+9
Irrigations after 2/3 depletion (2)								
0.09	1	+ 29.0	− 4.7	− 7.7	− 7.6	−4.3	−4.2	+2
	2.5	+ 55.5	−12.4	−28.6	− 9.2	−4.1	−3.6	−4
	4	+ 88.3	−27.5	−49.0	− 8.6	−4.2	−3.7	−5
0.18	1	+ 35.9	+ 2.1	−19.2	− 7.1	−5.2	−5.2	+3
	4	+109.9	− 3.7	−84.0	−10.8	−4.3	−4.6	+2
0.27	1	+ 45.8	+ 0.5	−24.8	− 7.8	−5.3	−6.6	+4
	2.5	+ 88.1	− 5.9	−54.4	−11.8	−4.9	−5.7	+6
	4	+135.3	− 2.2	−107.1	−10.5	−4.8	−5.5	+4

[a] A negative change in soil water salinity indicates salt was added to the soil profile; a positive value indicates a reduction.
[b] Closure = (salt in − salt out) 100/salt in.

TABLE IV

Relative dry mass of tall fescue clippings for each treatment throughout the experiment; daily irrigation with irrigation water having an electrical conductivity of 1 dS/m and with a leaching fraction of 0.27 was taken as the control treatment

Treatment		Prior to treatment	Salination period	Treatment period			
Leaching fraction	Irrigation salinity (dS/m)	1976—77	1977—78	1978—79	1979—80	1980—81	3-year mean
Daily irrigations(0)							
0.09	1	1.02	0.96	0.82	0.74	0.76	0.77
	2.5	0.98	0.91	0.98	0.80	0.72	0.83
	4	1.07	1.06	0.76	0.73	0.66	0.72
0.18	1	1.04	0.90	0.91	0.93	0.89	0.91
	4	1.02	0.97	0.87	0.80	0.76	0.81
0.27	1	1.00	1.00	1.00	1.00	1.00	1.00
	2.5	1.05	0.91	0.96	0.91	0.89	0.92
	4	1.02	0.92	0.90	0.73	0.96	0.86
Irrigations after 1/3 *depletion* (1)							
0.09	1	1.02	1.01	0.92	0.78	0.66	0.78
	4	1.02	0.87	0.78	0.61	0.45	0.61
0.18	2.5	1.02	0.95	0.86	0.79	0.78	0.81
	2.5	1.04	0.88	0.85	0.71	0.75	0.77
	2.5	1.04	0.95	0.96	0.76	0.75	0.82
	2.5	1.02	0.95	0.92	0.84	0.78	0.85
0.27	1	1.09	0.95	0.98	1.00	1.00	0.99
	4	1.04	0.98	0.90	0.92	0.95	0.92
Irrigations after 2/3 *depletion* (2)							
0.09	1	1.02	0.95	0.85	0.80	0.68	0.78
	2.5	1.00	0.96	0.72	0.82	0.65	0.73
	4	1.01	1.09	0.86	0.82	0.57	0.75
0.18	1	1.09	1.18	1.01	0.95	0.86	0.94
	4	1.02	0.91	0.82	0.86	0.65	0.78
0.27	1	1.04	0.92	0.96	0.95	0.96	0.96
	2.5	1.01	0.93	0.84	0.87	0.94	0.88
	4	1.01	0.87	0.82	0.93	0.82	0.86
Absolute yield of control treatment, kg/m^2							
0.27	1	1.23	2.30	2.12	1.94	2.12	2.06

given for the control treatment (0, 0.27, 1). Relative yields prior to initiation of the experimental treatments ranged from 0.98 to 1.09; only one treatment had a lower yield than the control before the experiment began. The standard error of the mean yield was 0.026 and there were no significant yield differences among plots prior to initiation of the treatments.

Having started with well-watered, nonsaline soil profiles, one year was allowed after the treatments were initiated for salination and crop response to the treatments. During this salination period, the fescue was harvested 21 times and the yield of all but four treatments dropped below that of the control. The yield of all treatments was high. The lowest yields were only 12 to 13% below that of the control. Two of the treatments (0, 0.09, 4 and 2, 0.09, 4) that would later suffer significant yield loss outyielded the control. This slow response illustrates the need for prolonged experiments when beginning with a well-watered, nonsaline soil profile.

Treatment effects on fescue dry matter yield were measured continuously for 3 years following the salination period. The yield of many treatments decreased with successive years; see, for example, treatment (2, 0.09, 1). The unstressed treatments (0, 0.27, 1; 1, 0.27, 1; and 2, 0.27, 1) maintained high production. A response surface analysis indicated that yield decline over time was highly significant (P = 0.0001). The response surface analysis also indicated that leaching fraction and irrigation water salinity influenced dry matter production significantly (P = 0.0001). Irrigation frequency, however, had no significant effect (P = 0.66). The largest time-averaged dry matter production was for the control treatment (0, 0.27, 1) with an average annual yield of 2.06 kg/m^2 but the yield was not significantly different for the unstressed, 1/3 depletion (2.04 kg/m^2) or the 2/3 depletion treatments (1.98 kg/m^2). The smallest yields were from a combination of low leaching (0.09) and high irrigation water salinity (4 dS/m) with average annual yields of 1.48, 1.26, and 1.54 kg/m^2 for the 0, 1/3, and 2/3 depletion treatments, respectively.

Root density. The influence of the three experimental factors on root distribution at the conclusion of the experiment is illustrated in Fig. 6.

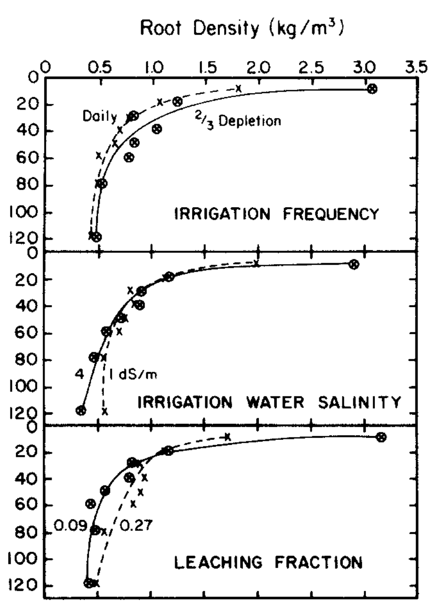


Fig. 6. Influence of irrigation frequency, irrigation water salinity, and leaching fraction on the density of fescue roots.

Root density, kg of dry roots per m^3 of soil, was relatively high at deep soil depths. The root zone of fescue under saline conditions has been reported to be 90 to 120 cm (Bower et al., 1970). Roots were found here to a depth of at least 120 cm. For all treatments, the distribution of roots appears to be exponential.

The total amount of roots per unit of soil surface area was influenced significantly (P = 0.05) by irrigation frequency. Treatments irrigated when soil water had been depleted by 2/3 had consistently higher root masses (1.4 kg/m^2) than the daily irrigated treatments (1.0 kg/m^2). Neither leaching fraction nor irrigation water salinity significantly affected total root mass which averaged 1.2 kg/m^2. Root distribution, however, appeared to be influenced. Reduced leaching (0.27 vs 0.09) or increased water salinity (1 vs 4 dS/m) increased the root density shallow in the soil profile with a corresponding reduction deep in the profile.

DISCUSSION

Water use — crop yield models

Models based on the assumption that crop production is directly proportional to evapotranspiration are confirmed by this experiment (Fig. 7).

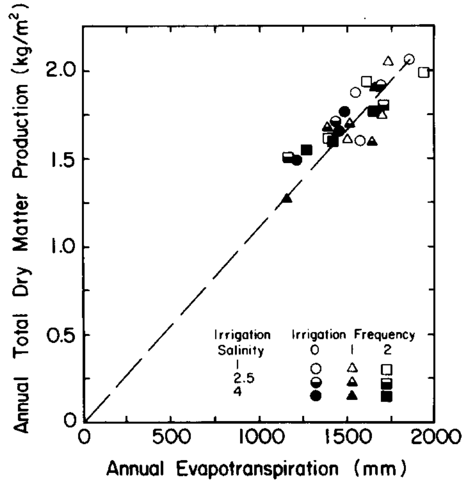


Fig. 7. Accumulated fescue dry matter production for 3 years (May 1978 to May 1981) as a function of annual evapotranspiration.

For semi-arid areas of the world, De Wit (1958) proposed that dry matter yield (Y) was related to transpiration (T) by:

$$Y = m\ T/E_0 \qquad (1)$$

where E_0 is the average seasonal free water evaporation rate and m is a crop factor. Building on this equation, Hanks (1974) proposed that for a given crop and a given year the factors m and E_0 are constant and thus relative yield is equal to relative transpiration,

$$Y/Y_p = T/T_p, \qquad (2)$$

where Y_p is potential yield when transpiration is equal to potential transpiration (T_p), defined as that transpiration which occurs when soil water is not limiting. Stewart and co-workers (1973, 1974, 1975) expanded this approach to include evaporation. Their basic equation for dry matter production is

$$Y/Y_m = 1 - B_0 + B_0 E_t/E_{tm} \qquad (3)$$

where Y_m is maximum yield when actual evapotranspiration (E_t) equals maximum (E_{tm}), and B_0 is the slope of relative yield (Y/Y_m) versus ($1 - E_t/E_{tm}$). Hanks (1974) noted that the ratio E_t/E_{tm} where Y/Y_m is zero is approximately the portion of E_{tm} that is due to soil evaporation. Thus, a value of 1.0 for B_0 indicates no evaporation.

The results of this experiment, presented in Fig. 7, indicate that soil evaporation was negligible because the relationship goes through the origin. In fact a least-squares linear fit of the data points has a positive Y intercept. Negligible soil evaporation is not unexpected because the fescue was mature and clipped to a height of 6 cm at harvest. Thus, equation (2) is directly applicable with annual Y_p being 2.06 kg/m^2 when annual T_p is 1850 mm. In equation (3) B_0 is 1.0. In equation (1) if E_0 is taken as pan evaporation (E_p = 1825 mm) and because $T = E_t$ here, m is essentially equal to Y because T/E_0 is approximately 1.0.

Salt tolerance model

The salt tolerance reported by Maas and Hoffman (1977) for tall fescue was $Y_r = 100 - 5.3\ (\bar{\sigma}_e - 3.9)$ where $\bar{\sigma}_e$ is the average electrical conductivity (dS/m) of soil saturation extracts for the crop root zone. The salt tolerance model is applicable where water is not limiting because L approaches 0.5 in salt tolerance experiments. Thus, this model should be an upper bound for the yield versus soil salinity relationship for this experiment because all L treatments were below 0.5. This is demonstrated to be true in Fig. 8 where the salt tolerance curve and the relative yield of each treatment are presented as a function of the average electrical conductivity of the soil water ($\bar{\sigma}_{sw}$). The salt tolerance curve was adjusted assuming $\bar{\sigma}_{sw} = 2\bar{\sigma}_e$. The mean of the salt sensor readings through the soil profile, integrated over time, was taken as $\bar{\sigma}_{sw}$ for each plot. Where water is limiting, as for many of these treatments, this value of $\bar{\sigma}_{sw}$ may not represent the salinity level to which the crop is responding. Suffice it to say here that if $\bar{\sigma}_{sw}$ had been calculated based upon water uptake distribution its

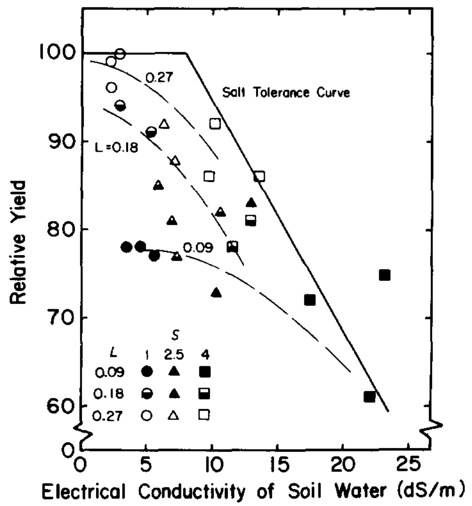


Fig. 8. Relative yield of tall fescue as a function of the average soil salinity in the root zone for each treatment. The curve depicts the salt tolerance of tall fescue.

value for many treatments would be less. If water uptake distribution can be approximated by root density distribution (Fig. 6), then the calculated $\bar{\sigma}_{sw}$ would be less because of the large fraction of water uptake shallow in the profile where soil salinity is lowest. If one were to draw curves through the data points based upon L and thus as a function of matric potential, the curves would be similar to those presented by Bresler et al. (1982) in their fig. 75 for the relative quantity of applied water. These data are now being applied to the Bresler model.

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