Physiological response of two turfgrass species to increasing drought and salinity stress using a line source gradient

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ABSTRACT

A line source gradient study was initiated to investigate the feasibility of using the saline aquifer, existing beneath the Las Vegas valley, as an alternative irrigation source for turfgrass. Results indicated that the aquifer could be used as a supplemental irrigation source, without any diminished turfgrass quality, if total water potentials ($\Psi_t$) were maintained above species specific thresholds, where $\Psi_t$ is defined as the sum of the matric ($\Psi_m$) and osmotic ($\Psi_n$) potentials. The soil water potential components ($\Psi_m, \Psi_n$) were found to additively affect yield, evapotranspiration, turf color, percent cover, and turf temperature. Leaf xylem water potential, stomatal conductance, and tissue osmolality responded to the interactive effects of $\Psi_m$ and $\Psi_n$. Water use efficiency decreased with increasing salinity in tall fescue but not in bermudagrass. Tissue ion concentrations remained unchanged with increasing $\Psi_t$ in bermudagrass, while all ion concentrations in tall fescue, except K, increased with increasing $\Psi_n$ and $\Psi_t$. 
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CHAPTER 1

INTRODUCTION

The population in the Las Vegas Valley is projected to possibly reach two million people during the next twenty years. Water use during this time is expected to increase 67% (Las Vegas Valley Water District, personal communication) based on water conservation programs already in place. New water conservation programs must be developed to help offset this projected increase in water use. A substantial amount of the municipal water budget in the Las Vegas valley is expended on landscape irrigation. Large turfgrass areas like golf courses, parks, and schools represent a significant percentage of urban landscapes in the arid southwestern United States. Therefore, a significant amount of potable water could be conserved if non-potable water sources were substituted for the irrigation of these large turfgrass areas.

A perched saline aquifer exists beneath the Las Vegas valley that could potentially be used as an alternative irrigation source. Before the aquifer can be used as an irrigation source on a large scale, the physiological response of turfgrass to this water must be studied over a
range of soil matric ($\Psi_m$) and osmotic ($\Psi_n$) conditions. In particular, the physiological tolerance limits of turfgrass species to both matric and osmotic stress must be quantified. This would include monitoring changes in yield, evapotranspiration, turf temperature, stomatal conductance, water use efficiency and tissue ion concentrations.

Reductions in yield of a crop irrigated with non-potable water could lead to reduced profits for the farmer. However, turfgrass growers are uninterested in total yield and are concerned primarily with the aesthetic appearance of the grass (turf color and cover). Further water savings could be realized if deficit irrigation techniques were employed, such that irrigation water was applied below the species' evapotranspiration rate. Changes in turfgrass quality to a range in salinity and drought would determine the minimum irrigation regime that could be used when irrigating with saline water that would still produce a grass stand acceptable to the grower.

The purpose of this study was to determine the physiological response of common bermudagrass (*Cynodon dactylon* L. 'Numex Sahara') and tall fescue (*Festuca arundinacea* Schreb. 'Monarch') to a range in total soil water potential ($\Psi_T$) values comprised of varying combinations of soil matric ($\Psi_m$) and soil osmotic ($\Psi_n$) potentials. The feasibility of using the saline aquifer in the Las Vegas valley as an alternative irrigation source was
then assessed based on the physiological response of the plants.

**LITERATURE REVIEW**

**Irrigation with Marginal Quality Water**

Irrigation with water of marginal quality is becoming more common in arid regions of the world. Common non-potable water sources include secondary effluent, reclaimed drainage water, power plant blowdown water, and ground water of poor quality. These water sources are often moderately high in soluble salts. Therefore, several important management issues must be considered before initiation of any irrigation program which utilizes marginal quality water.

First, the plant grown must be tolerant of the salinity level present in the irrigation water (Shalhevet 1994). Maas and Hoffman (1977) defined salt tolerance "as the yield decrease expected for a given level of salinity in the root medium as compared with yields under non-saline conditions . . . under conditions simulating recommended cultural and management practices". Maas and Hoffman (1977) reviewed past research on salinity stress and determined the salinity threshold value for many species from grasses to crop plants. This threshold value defines the maximum salinity level that will not decrease yield. Beyond the threshold, yield will begin to drop with increasing salinity at a
species specific rate. Based on this threshold value, each species was categorized as sensitive, moderately sensitive, moderately tolerant, or tolerant. For example, orange trees are listed as being sensitive with a salinity threshold of 1.7 dS/m, tall fescue as moderately tolerant at 3.9 dS/m, and bermudagrass as tolerant at 6.9 dS/m (Maas and Hoffman 1977).

The Maas and Hoffman (1977) model only applied to well watered conditions where the leaching fraction was maintained at approximately 0.50, indicating that 50% of the irrigation applied was lost as drainage. Irrigation practices today need to be more efficient because water resources are too limiting to allow half of the water to be lost as drainage. Further, application of saline water with high leaching fractions leads to substantial salt loading of the surrounding water shed (Rhoades et al. 1989, Rhoades 1983).

Detrimental salt accumulation in the root zone of the soil with use of saline irrigation waters can be mediated through proper management practices. These practices include altering the frequency of irrigation, adjusting the leaching fraction, and cycling the use of saline and non-saline waters.

It has been generally accepted that the frequency of irrigation should be increased when irrigating with saline water (US salinity staff 1954). It is thought by many that
increased irrigation frequency will maximize yields by keeping the soil moisture constantly high while maintaining continuous drainage through the soil profile. Experimental data has supported and disputed this assumption.

Biren et al. (1981) found that yield did significantly decrease in eleven turfgrasses if the irrigation frequency was reduced from three irrigations per week to one. Devitt et al. (1991) also found that decreased irrigation frequency correlated with decreases in yield of bermudagrass on sandy and silt loams, regardless of salinity level. However, the bermudagrass grown on clay soil exhibited the opposite trend. This opposing trend may have been due to poorer leaching and/or aeration within the clay soil.

Bradford and Letey (1992a), on the other hand, found that cotton responded to the total weekly amount of water applied and not the weekly irrigation frequency. Hoffman et al. (1983) also found that irrigation frequency did not affect the dry yield of tall fescue. They found instead that the grass responded to the leaching fraction and the salinity of the irrigation water.

Another management factor that should be considered is leaching required. If leaching is eliminated, salts will continue to accumulate in the soil, eventually to levels unsuitable for plant growth. The “leaching requirement” is defined as the amount of water that must pass through the root zone to maintain the salinity level of the root zone
within tolerance limits of the plant grown. It is important to know the leaching requirement of the chosen plant to calculate an efficient irrigation regime that will maintain soil salinity levels while minimizing the amount of water lost to drainage (Shalhevet 1984, Rhoades et al. 1989, Rhoades 1983, Jury et al. 1978)

The two factors determining the leaching requirement is the salinity of the irrigation water and the salt tolerance of the plant. The leaching requirement model is as follows:

$$L_r = \frac{q_d}{q_i} = \frac{C_i}{C_d}$$

where q is the volumetric flux of water and C is the water salinity, i and d are irrigation and drainage respectively. As the salinity of the irrigation increases or the salt tolerance of the species grown decreases, the leaching fraction must be increased to maintain a desired level of productivity. Salinity sensors and tensiometers in the soil are often used to calculate the leaching requirement (Hoffman and Jobes 1983, Jury et al. 1978). However, salts are rarely uniform within a soil column and the travel time from the surface to a depth below the rootzone often make salinity sensors impractical for short term irrigation calculations. An evapotranspiration feedback system that accounts for short term changes in plant water use via empirical models based on climatological data may be more appropriate for scheduling irrigation to maintain a chosen leaching fraction (Devitt et al. 1992).
Seasonal irrigations with fresh and saline waters can prevent the salinity level within the soil from becoming too excessive while still allowing low quality water to be utilized at least 50% of the time (Bradford and Letey 1992b). Crop rotations associated with changing water quality can help offset yield reductions. Salt tolerant plants can be grown during one season with saline water, followed by the growing of a more salt sensitive species the next season with good quality irrigation water (Bradford and Letey 1992b, Pasternak et al. 1986, Rhoades et al. 1989).

Cycling irrigation waters is another practice that can be used when irrigating with water containing appreciable levels of soluble salts. This practice involves irrigating a crop with fresh water during the more salt sensitive physiological periods and with saline water during the more salt tolerant periods or by cycling fresh and saline waters on and off the field at cycle rates that would maintain soil ECₑ values below threshold values. Germination and seedling establishment stages are usually the most salt sensitive growth periods (Pasternak et al. 1986). Pasternak et al. (1986) found that saline irrigation at germination of tomato significantly decreased growth at later stages. However, if non-saline water was applied until the appearance of the fourth or later leaves, a substantially smaller decrease in yield was observed (only 30% yield reduction as compared to 60% when irrigation with saline water from seed). Lastly,
saline water can be blended with non-saline water to bring the salinity level below the crop salt tolerance threshold (Rhoades 1983, Bradford and Letey 1992b).

The selection of an appropriate irrigation management program when using marginal quality water can be quite complex. Site specific characteristics (soil type, humidity, temperature, soil fertility, amount of precipitation, depth to water table, drainage, topography, etc.) may require the management program to be altered from site to site for a specific species. Further, it needs to be determined how the water should be applied (sprinklers, drip lines, etc.) to be most beneficial to the plant (Shalhevet 1994). Interactions, therefore, between irrigation frequency, soil type, soil fertility, salinity of the irrigation water, salinity of the soil, and the stress tolerance of the vegetation should be considered before an appropriate irrigation schedule and management program is implemented.

**Line Source Gradient Methodology**

The line source gradient procedure was developed to allow researchers the ability to create a range in water deficit conditions over a reasonable experimental plot size (Hanks et al. 1976, Hanks et al. 1980). It involves an irrigation line with evenly spaced sprinkler heads that creates a gradient of linearly decreasing irrigation volumes.
with distance away from the irrigation source. The irrigation treatment can be replicated twice because the same gradient exists on both sides of a single line source.

This procedure is commonly used to assess the drought response of many different plants. A line source drought experiment has been performed on corn and cowpea (Fadohunda 1985), corn (Barragon and Recasens 1988), rice (Blackwell et al. 1985, Novero et al. 1985), pearl millet (Ibrahim et al. 1985), for greenhouse plant breeding and drought resistance selection (Johnson et al. 1982), sorghum stalk rot resistance and drought response (Seetharama et al. 1987), cowpea (Tyem and Chieng 1985) and legumes (Lockerman et al. 1989).

This procedure also allows additional parameters to be studied in strips perpendicular to the irrigation treatment (Hanks et al. 1980). Various nitrogen levels have been placed in random strips perpendicular to the irrigation source to assess interactions between nitrogen fertilization and water stress (Aragon and De Datta 1982). Many other possible parameters can be examined perpendicular to the line source, such as different species or cultivars to compare drought tolerance, application of various levels of macro- or micronutrients, disease resistance via application of pesticides and water quality to list a few.

The single line source technique was later modified into a double line source to determine separate and
interactive effects of water deficit and water quality (Frenkel et al. 1990, Broadbent et al. 1988). This modification includes two parallel irrigation lines placed at a distance apart to prevent any overlap based on the wetting radius of the sprinkler heads. One line typically is set up to irrigate non-saline water while the other line would be set up to irrigate saline water. This technique produces a water deficit gradient in the non-overlap region of the fresh line, a salinity gradient in the middle of the two lines, and a salinity/drought gradient in the region receiving only saline water. The physiological response of the plant can then be evaluated based on a range in water deficits, salinity, and both water deficit and salinity (Broadbent et al. 1988).

The line source method was also modified into a triple parallel design (Arnold et al. 1987, Aragues et al. 1992). This design consisted of three parallel irrigation lines spaced evenly apart at a distance equal to the wetting radius of the sprinkler heads. Further, the outside two lines receive the same water type while the middle line is the treatment line. The middle line could contain saline water (Aragues et al. 1992), herbicide (Arnold et al. 1987), fertilizer, or other irrigation related variable of interest. This design eliminates the water deficit gradient by irrigating the same quantity of water over the plots between the lines. The center irrigation line creates the
gradient of interest. Therefore, plant response to various levels of salinity, fertility, or herbicide concentration can be studied in detail.

The final modification to the line source method was the triple-crossed line source design (Magnussen and Ben-Asher 1990, Steynberg et al. 1989). Three parallel irrigation lines are crossed with three perpendicular irrigation lines, again evenly spaced apart at a distance to prevent any overlap. The two outside lines in each direction are typically irrigated with non-saline water while the middle lines irrigate with treatment water. One possible design combination tested included one line being irrigated with saline water while the other line irrigated with non-saline water with a nitrogen addition (Magnussen and Ben-Asher 1990, Steynberg et al. 1989). A nitrogen gradient would thus be superimposed perpendicular to the salinity gradient between the lines. Therefore, all possible combinations within the range of irrigation waters applied are created to assess the separate and interactive effects of nitrogen concentration and salinity.

One problem that has been expressed by many authors is wind. Wind, predominately from one direction, causes increased variability in the gradients produced. However, if irrigations are planned for times of low wind the effect of wind can be minimized.
A major disadvantage of the line source method is that the irrigation treatments are not random. They are systematically applied over the plot (Hanks et al. 1980). This arrangement has no statistical test to assess the significance of the irrigation effect. However, tests on the treatments at right angles to the line can be compared statistically (Fernandez 1991). A split block statistical design can be used with the treatment as the main plot and irrigation level as the subplot (Hanks et al. 1980).

The line source method and its modifications have enabled researchers to assess the physiological response of a plant to various degrees of stress and/or other variables such as fertility. Further, this design allows the use of plots that are of reasonable size and cost to be maintained. Therefore, this approach will remain popular in plant studies where resources are often limited.

**Physiological Responses to Salinity**

Irrigating with poor quality waters can increase the salinity of the soil solution and can lead to many adverse physiological responses in the plants being grown. Although there are general responses to increasing salinity, different cultivars within the same species can vary in the extent of the response to elevated salinity. *Phaseolus vulgaris* (bean) has been shown to have a reduction in yield at an ECe of 1.0 dS m\(^{-1}\) while an ECe of 6.9 dS m\(^{-1}\) has been
reported to be the threshold for a decrease in the growth of *Cynodon dactylon* (bermudagrass) (Maas and Hoffman 1977). Therefore, the response to increasing salinity of the species and/or cultivar chosen needs to be known in depth before any plan to utilize poor quality water is implemented.

The first observable response to salinity is a decrease in the growth rate or dry weight accumulation of the plant (Ackerson and Younger 1975, Devitt et al. 1987, Dudeck and Peacock 1985, Francois 1988). This response has been shown to be common to many plants, once the species specific salinity threshold is exceeded (Maas 1986). However, careful evaluation of research methodology is necessary to distinguish between single ion toxicity and a general osmotic response. For example, Bogemans et al. (1990) found that barley grew slower if salinity was increased. However, their methodology involved the use of only NaCl. A single salt solution may elicit species specific responses to a specific ion. In such a case, the plant response may have been due to sodium or chloride toxicity as opposed to increased solution osmotic potentials.

Bermudagrass and other C₄ plants typically have a high tolerance to salinity. The allocation patterns of carbon resources are adjusted to increase root growth while slowing shoot growth (Ackerson and Younger 1975, Dudeck et al. 1983,
Marcum and Murdock 1990, Meyer et al. 1989). Dudeck et al. (1983) found that an ECe of 4.52 dSM$^{-1}$ led to a 10% decrease in shoot growth while a 168% increase in root growth in bermudagrass. An ECe of 9.9 dSM$^{-1}$ caused a 20% reduction in shoot growth but a 270% increase in root growth over the no salt treatment. Beyond the species salinity threshold, both root and shoot growth rapidly decreased. No mortality was noted until the EC of the hydroponic solution was over 32.5 dSM$^{-1}$. However, this study was done hydroponically in a single salt solution enriched with a nutrient supplement. Therefore, caution should be taken when applying these results to a soil based, field system. A shift in the root/shoot ratio under saline conditions could lead to root systems extending deeper into the soil profile, perhaps into areas where the soil solution has a more favorable ionic/osmotic status. Thus, partially mediating the effect of elevated salinity levels found in surface soils. However, increased root growth was not found in seashore paspalum grasses (Dudeck and Peacock 1985) and four species of flowering annuals (Devitt et al. 1987).

The direct cause for a reduction in yield has not been clearly resolved. An osmotic effect may reduce yield by creating lower soil water potentials, making water more difficult to extract from the soil. Therefore, the plant must expend energy for the uptake of ions in the soil solution or produce organic solutes to maintain lower
cellular water potentials than is found in the rhizosphere. This process is termed osmotic adjustment. Either process (ion uptake or production of organic solutes) will maintain cellular turgor and a more negative cellular water potential than is found in the soil, facilitating the uptake of water. However, increased ion uptake may disrupt normal cellular biochemical processes like protein synthesis, DNA replication, and photosynthetic pathways (Greenway and Munns 1980, Aspinal 1988, Kriedemann 1988). Increased soil salinity may also directly or indirectly cause stomatal conductance to decrease. Thereby, reducing gas exchange and photosynthesis. A combination of these responses is most likely the true cause of diminished growth and yield.

Osmotic adjustment is an energy requiring process. Therefore, photosynthates are shifted from growth to active ion uptake processes and/or organic solute production. Ions imported into the cell are usually sequestered into the vacuole. This reduces the chances of negative effects from ion toxicity on cellular organelles and enzyme activity in the cytoplasm (Rendig and Taylor 1989). Most DNA replication and protein synthesis slows with increasing salinity (Aspinall 1988). Organic solutes, on the other hand, are produced in the cytoplasm because they are more compatible to cellular biochemical processes (Kriedman 1988).
Terrestrial plants grow in soil solutions containing salts of mixed ionic status. Any ion is capable of acting as an osmoticum but also capable of disrupting normal cellular functions if concentrations are too high.

Sodium can replace calcium in cell walls and membranes, reducing the permeability and selectivity of membranes, which can lead to increased toxic effects associated with specific ions (Greenway and Munns 1980). Adequate calcium has been shown to ameliorate some of the adverse effects of high sodium concentrations. Calcium has been shown to prevent decreases in root growth of cotton (Kurth et al. 1986) and maintain the integrity of membranes of corn root cells (Lynch et al. 1987). Sodium can also interfere with the uptake of potassium. Potassium concentrations in leaves tend to drop as soil sodium concentrations increase (Marcum and Murdock 1990). Potassium is the primary ion used to balance the negative charges of sulfate, nitrate, phosphate, chloride, and organic solutes for long distance transport within the plant (Flowers and Yeo 1988). Potassium also has important roles in enzyme and photosynthetic reactions and development of structural components within the cell (Rendig and Taylor 1989). Potassium also plays an important role in regulating stomatal opening and closing. Therefore, the adverse effect of sodium replacing potassium can have severe consequences. However, excess potassium salts can also have adverse effects on cellular metabolism as well.
Accumulation of ions at the cell wall can have an adverse effect on surrounding cells (Flowers and Yeo 1988). This accumulation of ions can result in a localized reduction in water potential that pulls water out of neighboring cells. This potentially results in cellular dehydration, loss of turgor, and death. Therefore, ions must be accumulated continuously in the protoplast from the xylem to prevent the loss of water from the cell (Flowers and Yeo 1988).

Photosynthetic inhibition has been noted in many species in response to salinity. This diminished photosynthesis could be due to decreased gas exchange (stomata partially open or completely closed), depression of the biochemical capacity for carbon assimilation, or a decrease in photosynthetic capacity. One or more of these factors would lead to yield reduction due to diminished carbon assimilation.

Bowman (1987) found that *Andropogan glomeratus*, a C₄ non-halophyte, decreased carbon dioxide uptake with increasing salinity levels. Corresponding decreases in stomatal conductance was observed. However, stomatal conductance only played a partial role in reducing photosynthesis. Biochemical inhibition also played a role. Bowman (1987) also found a decrease in carboxylation efficiency, interpreted as a decrease in Rubisco activity or
inefficiency in the C₄ pathway at increased levels of salinity.

Downton et al. (1985) found similar results in spinach. A drop in stomatal conductance and internal carbon dioxide concentrations resulted in decreased photosynthesis. The authors attributed this response to biochemical inefficiency and morphological changes in leaf structure. Leaves produced under saline conditions tend to be thicker and more succulent than those produced under non-saline conditions (Downton et al. 1985, Meyer et al. 1989, Kriedeman 1988). Downton et al. (1985) found that leaves produced under stress associated with salinity were 70% thicker and contained 73% of the chlorophyll of the control plants per area (46% on a fresh weight basis). Thicker leaves make it harder for carbon dioxide to diffuse into the tissue containing the chloroplasts. The authors also found in this study that photosynthesis at the chloroplast level was maintained, therefore, was not chemically limited.

As stated previously, growth is typically slowed with increasing salinity. Decreased production of new photosynthetic tissue leads to decreased leaf area, and often decreased assimilation per unit leaf area, and increased maintenance respiration.

Plant responses to salinity are complex. Ion accumulation disrupts membrane selectivity and biochemical reactions as well as water relations at the cellular and
whole plant level. Limitations to gas exchange decrease the photosynthetic capacity and ultimately growth. Which response occurs first and how the reactions are interrelated is difficult to discern. The responses may be circular (i.e. an increase in ion accumulation decreases photosynthesis which decreases growth which increases ion concentrations in existing tissues, etc.).

Most salinity studies are short term experiments on established seedlings. Further, a good proportion of salinity research is done hydroponically to eliminate matric effects. Long term experiments are needed that investigate the plant's integration of salinity stress through all growth stages. For example, perennial ryegrass was found to be more salt tolerant at germination than at later growth stages (Dudeck and Peacock 1985).

**Physiological Response to Drought**

Drought stress, like salinity stress, results in a reduction in growth, when species threshold values are exceeded. Yield reductions to increasing water deficits were observed in rice (Aragon and De Datta 1982, Blackwell et al. 1985, Novero et al. 1985, Turner et al. 1986), corn (Barragen and Recesens 1988), maize and cowpea (Fadohunda 1985), pearl millet (Ibrahim et al. 1985), perennial ryegrass (Bittman and Simpson 1987), and sorghum (Devitt et al. 1986). However, the mechanisms involved in the
reduction in growth are often different for drought stress than for salinity stress.

Decreases in soil matric water potential elicit a series of physiological and biochemical responses, starting with the perception of stress (Bray 1993). These responses include decreased growth, photosynthesis, stomatal conductance, protein synthesis, and increases in organic acid production. However, these responses depend on the severity and length of the stress, plant species, developmental stage, and other environmental constraints on growth (Chaves 1991).

Water deficit stress occurs when transpiration water loss exceeds water absorption by the roots (Kramer 1983). Growth is severely limited by drought when both reductions in cellular division and cell enlargement due to turgor losses occur (Barlow 1986). A minimum level of turgor must be maintained within an expanding cell to produce an "over pressure" that exceeds the wall yield threshold to continue growth (Richter and Kikuta 1989).

The plant's turgor is maintained by osmotic adjustment (Bray 1993, Jones and Turner 1978, Richter and Kikuta 1989). Osmotic adjustment is the active accumulation of solutes in tissue to maintain negative water potential gradients from the soil to the stomata. Two mechanisms can produce this gradient. Inorganic ions can be absorbed from the soil and accumulated in the cells. This mechanism is prevalent in
plants grown under saline conditions. Drought stress can also facilitate an increased uptake of inorganic ions through the concentrating of salts in the soil solution as the soil matric potential drops (McCree 1986). However, osmotic adjustment under drought stress usually involves the production of organic solutes in the leaves. The production of organic solutes presents an additional carbon cost to the plant. Therefore, another reason growth could be diminished under drought is that photosynthate reserves are shunted to turgor maintenance and away from the production of new cells or new material for expanding cells.

Growth slows before any major reduction in either stomatal conductance or photosynthesis is noted (Kriedemann 1988). In sunflower, leaf growth slowed at a leaf water potential of -0.4 MPA while stomatal conductance remained unchanged until a leaf water potential of -0.8 MPA was reached (Kriedeman 1988). Decreased turgor was the cause for the reduced growth in the short term. Long term drought detrimentally affects stomatal conductance and photosynthesis.

Decreased photosynthesis in response to drought has been attributed to both stomatal and non-stomatal limiting factors (Chaves 1991). Stomatal closure, either partial or complete, is the first line of defense against cellular dehydration (Chaves 1991). But, there is a cost involved with the protective mechanism of the stomates. Stomatal
closure also limits carbon assimilation (growth and metabolism). Photosynthates must be produced at a rate that supports continued growth and maintenance. Therefore, a decrease in gas exchange will eventually decrease growth.

Non-stomatal limitation of photosynthesis also negatively impacts growth. Non-stomatal limitations involve a malfunction at the photosynthetic apparatus level. Ehleringer and Cook (1984) found that leaf water potentials decreased the photosynthetic rate, stomatal conductance, and carboxylation efficiency in *Encelia farinosa*. The authors suggested that a coordinated response between the stomata and photosynthetic apparatus exists in response to decreases in leaf water potential. The stomata responded quickly to a water deficit while non-stomatal components responded more slowly to extended drought (Ehleringer and Cook 1984).

This mechanism allows the plant to respond to short term changes in water potentials without decreasing photosynthesis. The stomata can open and close in response to slight fluctuations in water potentials, which are usually temporary and short term, without any permanent changes in photosynthetic biochemical activity. The photosynthetic apparatus responds to extended and more pronounced droughts by initiating protective mechanisms to prevent serious permanent damage.

The cost of the protective mechanisms is decreased photosynthetic efficiency. Permanent damage to the
photosynthetic pathway can also be caused by the inhibitory effects of increased cellular solute concentration on enzyme activity (Kaiser 1982). Specifically, increased concentrations of sulfate or phosphate and stroma acidification may be the cause of decreased efficiency (Kaiser et al. 1986).

**Combined Salinity and Drought Effects**

Plants grown under field conditions experience both salinity and drought conditions simultaneously, especially when irrigating with water containing soluble salts. The physiological response depends on how the plant integrates both matric and osmotic stress. Most studies investigate drought or salinity stress independent of the other. Most salinity stress studies are performed under well watered conditions to eliminate the effects of changes in $\Psi_m$. Water stress studies, conversely, use waters with low concentrations of soluble salts to minimize any osmotic effects. However, this poorly correlates with what often occurs in natural settings. Few studies have tried to separate $\Psi_t$ into its components, $\Psi_m$ and $\Psi_n$ to investigate any interactive effects.

Salinity treatments, either as a pretreatment before imposed drought (Shalhevet and Hsaio 1986, Jensen 1982) or as a concurrent salinity and drought stress (Stark and Jarrell 1980, Parra and Cruz-Romero 1980, Devitt et al.)
1993, Hao and de Jong 1988), reduced the rate at which water was extracted from the soil. Therefore, the saline treated plants retained a favorable \( \Psi_m \) longer than fresh treated plants that extracted water at a significantly faster rate. A possible benefit of saline irrigations is that although yield is decreased, when compared to non-saline treatments, the plants are able to withstand a progressive drought for a longer period of time.

Barley has been shown to continue growing at a measurable rate when pretreated with saline irrigations at low \( \Psi_m \), whereas non-salt treated plants ceased to grow at moderate \( \Psi_m \) levels (Jensen 1982). The plants growing under saline conditions also maintained higher turgor pressures at a lower \( \Psi_m \) than was observed with plants irrigated with fresh water, due to greater osmotic adjustment occurring under salinity stress.

Stark and Jarrell (1980) also found that salinity induced responses that facilitated the maintenance of a more favorable water balance in maize. The authors used four salinity levels at well watered conditions then imposed a 35 day drought cycle on all treatments. The highest salinity level had the lowest elongation rate when drought was initiated. However, the highest salinity level maintained growth throughout the experiment while the no-salt treatment ceased to grow by day 35. The authors suggested that morphological adaptations to salinity reduced water
conduction and facilitated turgor maintenance through osmotic adjustment. On the other hand, drought preconditioning does not appear to enhance the performance of a plant placed under a salinity stress (Shalhevet 1993).

It has been assumed that since both $\Psi_m$ and $\Psi_n$ reduce the free energy of water that they must act additively in their effect on yield. However, the results of various studies have shown that the response of a plant to $\Psi_m$ and $\Psi_n$ is not that simple. Parra and Cruz-Romero (1980) used four salinity levels under two different irrigation regimes on beans to separate the effects of $\Psi_m$ and $\Psi_n$. The authors concluded that the effects of $\Psi_m$ and $\Psi_n$ were not additive. A one unit decrease in $\Psi_m$ led to a steeper decline in growth than was observed with a one unit decrease in $\Psi_n$, due to restricted water movement in the soil under lower $\Psi_m$.

Sepaskhah and Boersma (1979) also concluded that $\Psi_m$ and $\Psi_n$ were not additive. However, they used a single salt solution (NaCl) and a PEG solution (polyethylene glycol) to produce both an osmotic and water stress. Therefore, their results may be due to ion toxicity and/or the artificial conditions created by PEG.

Shalhevet and Hsiao (1986) concluded that $\Psi_m$ and $\Psi_n$ were additive on yield and water uptake of cotton and pepper, but only if turgor was maintained. They found, like Parra and Cruz-Romero (1980), that water stress led to steeper declines in $\Psi_l$, transpiration, assimilation, and
growth. They also found that the drought treated plants extracted more water from the soil than the saline treated plants. Therefore, salt treated plants were able to maintain a level of physiological activity for a longer period of time under a progressive drought (Shalhevet and Hsaio 1986). The water stressed-no salt plants also exhibited incomplete osmotic adjustment. Therefore, they were less able to maintain favorable turgor pressure. The authors also concluded that a one unit decrease in $\psi_m$ had a more detrimental effect to plant physiological processes than a one unit decrease in $\psi_n$.

Broadbent et al. (1988) used the line source technique to produce a water and salt gradient on sorghum and wheat. They also concluded that a unit decrease in $\psi_m$ had a greater effect on yield and nitrogen uptake than a unit decrease in $\psi_n$. Therefore, they concluded that $\psi_m$ and $\psi_n$ were not additive.

Opposing conclusions do exist. Frenkel et al. (1990) found no difference in the yield or evapotranspiration response of corn to either a fresh or salt double line source gradient. The plants were responding to $\psi_r$ regardless of the ratio of $\psi_m$ and $\psi_n$. They concluded that $\psi_m$ and $\psi_n$ were additive. The authors did note that "there is no indication that one unit of water stress is equal to a unit of salt stress".
Research has still not provided conclusive results on the effects of varying degrees of $\Psi_m$ and $\Psi_n$ on plant physiological processes. Studies using single salt solutions for salinity treatments or PEG for water stress typically investigate one stress independent of the other. Further, these techniques are often conducted in climate controlled growth chambers. Results from these studies may not be transferable to the field. Therefore, a species' response to salinity and drought should be assessed under field conditions. This process would provide better information for the development of best management practices to employ when using waste water as an irrigation source.
CHAPTER 2

TURFGRASS QUALITY, GROWTH AND WATER-USE
AS A FUNCTION OF SALINITY AND WATER
DEFICIT INDUCED STRESS

Abstract
Limited water resources in the arid southwestern United States have created greater interest on the part of municipalities to utilize poorer quality waters in the urban setting. Research was conducted to assess the feasibility of using a perched saline aquifer as an alternative irrigation source for turfgrass. Two line source gradient experiments, one using municipal water with an EC of approximately 1.1 dSm⁻¹ and the other using saline aquifer water blended with municipal water to an EC of 6.0 dSm⁻¹, were established to impose a salinity and/or water deficit gradient on tall fescue (Festuca arundinacea Schreb. 'Monarch') and an improved common bermudagrass (Cynodon dactylon L. 'Numex Sahara'). Growth, turf quality, and water use were monitored during a 68 day drydown period during the summer of the second year of experimentation.
Yield was found to be highly correlated with ETa (r=0.92, p<0.001 for bermudagrass and r=0.83, p<0.001 for tall fescue) regardless of how the stress was imposed (high-low salinity in combination with high-low water availability). Relative ETa values as a function of the summation of the leaf to air temperature differences also indicated no distinguishable change in the grasses' stress response based on water quality (r=0.94, p<0.001 for tall fescue and r=0.86, p<0.001 for bermudagrass). Relative turf color and percent cover remained unchanged if the ratio of irrigation volume to potential evapotranspiration (I/ETo) remained above species specific threshold values of 0.80 for tall fescue and 0.65 for bermudagrass. Below these thresholds, cover and color declined linearly with separation by water quality treatment in tall fescue but with no separation by water quality treatment in bermudagrass.

**Introduction**

In the arid southwestern United States, most large municipalities (Phoenix, Las Vegas, Tucson) are developing water conservation programs to help offset projected growth driven water consumption. Water use, in the Las Vegas Valley, is projected to increase 67% within the next 20 years based on using only conventional conservation programs (Personal Communication, Las Vegas Valley Water District 1995). New conservation programs must be developed to help
offset this projected increase in water use. Landscape irrigation, in particular, represents a sizable fraction of the total water used in most southwestern communities (Department of Conservation and Natural Resources 1982). Significant landscape water savings could be realized if poorer quality waters were substituted for irrigation purposes. Rhoades et al. (1989) indicated that waters previously thought unsuitable for irrigation can often be used successfully without hazardous long term consequences to crops or soils if proper crop/water management strategies are employed. As such, all water resources, including those currently classified as having poor quality, should be given a more serious consideration for incorporation into urban water conservation programs. Since most large municipalities generate significant amounts of sewage effluent, cooling tower blowdown water, industrial wastewater and/or possess poorer quality groundwater sources, the opportunity exists for utilizing such waters as alternative irrigation sources.

The successful use of waters containing high levels of soluble salts for irrigation of crops has been well documented during the last fifty years in the United States (Pasternak et al. 1986, Gratten et al. 1987, Broadbent et al. 1988, Rhoades 1983, Rhoades et al. 1989). Although irrigation with highly saline waters have not been reported under field conditions for turfgrass, it has been
demonstrated and accepted by turfgrass growers that turfgrass can be successfully irrigated with sewage effluent (Graves 1982, Hayes et al. 1990). It should also be noted that under small scale controlled studies, many turfgrass species have been shown to be more salt tolerant than many agricultural crops (Hoffman et al. 1983, Maas and Hoffman 1977).

Recently, the concept of working at the no-yield-loss threshold has been challenged by Letey et al. (1985) and Rhoades et al. (1989). They suggest that instead of irrigating to maximize yields, one should irrigate to maximize profits. This approach would justify using lower priced poorer quality waters even though some yield reductions might occur. However, with turfgrass, using lower quality waters will be linked not only to costs/profits but also directly to the decline in turf quality found tolerable. This would vary from little decline in quality found tolerable on most golf courses to higher amounts found tolerable on parks and schools. Clearly the use of poor quality waters will be driven by economic factors, as irrigators will typically not use poor quality waters unless good quality waters are inaccessible or the cost of good quality waters are high. Reports by Valentine (1984) have indicated that few farmers in the Imperial Valley have taken advantage of free drainage water because fresh water remains available at a reasonable cost.
In southern Nevada, the situation is becoming very different. As water prices continue to go up, the cost of water has become the largest operational budget item for most golf courses, parks, and schools. Water bills approaching one million dollars per year per golf course using municipal water are common. Such operational costs would suggest that the economic incentive to use low cost poorer quality waters exists, if it can be clearly demonstrated that only minimal loss in turf quality would occur. This research was therefore conducted to determine the potential of using a shallow saline aquifer as an alternative irrigation source for turfgrass under field conditions, by monitoring not only the yield water-use response but also the quality of the turfgrass when placed under combinations of salt and water deficit induced stress.

**Methods**

A two year study to investigate the potential use of a shallow aquifer as an alternative irrigation source was conducted at a research site in Las Vegas, Nevada. A line source water gradient experiment was carried out during the summer of each year (sixty-eight days each). Treatments consisted of decreasing irrigation volumes with increasing distance from the irrigation line source (Hanks et al. 1976). Two identical line source experiments were conducted at the same site, separated by a common buffer zone. One
line source received municipal water for irrigation (electrical conductivity EC = 1.1 dS m\(^{-1}\)) while the other line source received well water from a perched saline aquifer (blended to an EC of 6.0 dS m\(^{-1}\) with municipal water). Description of soil characteristics and ion concentrations in the irrigation water are reported in table 1. Each line source experiment was further divided into equal areas (northern and southern sections of field) containing either *Festuca arundinacea* Schreb. 'Monarch' (Tall Fescue) or *Cynodon dactylon* L. 'Numex Sahara' (common bermudagrass) which was overseeded with *Lolium perenne* L., varietal composition of 50% "Palmer", 50% "Prelude" (perennial ryegrass).

The irrigation system was comprised of six sprinkler lines spaced 13.4 m apart. Rotor pop-up sprinklers (Toro 700 series) were spaced 6.7 m apart on each line. All irrigations were applied at 0.41 MPa (60 psi) to give a wetted radius of approximately 13.4 m. During each summer of the study, the outer irrigation lines (fresh and saline) were disconnected, setting up a well defined line source gradient. The three lines on the west side of the field were used to irrigate saline water, while the three lines on the east side of the field were used to irrigate municipal water.

Lysimeters were used to quantify the evapotranspiration of the turfgrasses growing under the imposed treatments.
The lysimeters (51 cm diameter, 120 cm length) were all filled with the same blended surface soil taken from the field site to reduce soil variation between lysimeters. The soil was a fine-silty, mixed, thermic typic haplosalid (Table 1). Eighteen lysimeters were located in each of the water treatments, with nine lysimeters located in each turfgrass by water treatment area. There were four lysimeters per row at a spacing of 4.6 m, replicated twice. The ninth lysimeter per quadrant was placed at the 4.6 m position.

The lysimeters were equipped with two drainage extraction cups placed in the bottom of the lysimeters in 10 cm of diatomaceous earth. A metal access tube, located in the center of each lysimeter allowed a neutron probe to be lowered into the soil to estimate soil water content.

Nitrogen was applied to all turfgrass areas containing lysimeters at a rate of 48.9 Kg ha\(^{-1}\) month\(^{-1}\). Nitrogen applied to the saline part of the field was reduced to compensate for the background nitrogen level in the saline water.

Irrigation volumes were calculated from the equation \(I = \frac{ET_a}{1-LF}\), where \(I\) is the total irrigation for the week, \(ET_a\) is the actual evapotranspiration of the previous week and \(LF\) is the leaching fraction (drainage volume/irrigation volume). Actual evapotranspiration was calculated by the hydrologic balance approach (\(ET_a = \text{Irrigation volume} - \text{Drainage}\)).
volume-change in storage). Irrigations were applied four
days per week. Irrigation volumes applied to each lysimeter
were estimated after each irrigation by measuring the volume
of water that was collected in a catchcan placed at the
center of each lysimeter. Drainage volumes were collected
from each lysimeter by applying a vacuum (-0.0173 MPa) for
one hour, four days per week on the buried suction
extraction cups. Soil water in storage was calculated by
integrating estimated volumetric water contents over depth.
Calculated irrigation volumes were applied to the whole plot
at a rate to maintain a leaching fraction (LF) of 0.25 in
the lysimeter closest to the irrigation line source. Since
bermudagrass and tall fescue were located on the same line
source, irrigations were based on maintaining the 0.25 LF on
the tall fescue.

Total solar radiation, wind run, rainfall, daily
minimum and maximum ambient temperatures, as well as daily
minimum and maximum relative humidities were collected from
an automated weather station (Campbell Scientific, Model
012, Logan, UT). Daily potential evapotranspiration (ET₀)
was then calculated from these parameters by using a
modified Penman Combination Equation (Campbell Scientific,
Logan, UT).

Grass samples were harvested from each lysimeter on a
weekly basis. Tall fescue was cut at 5.1 cm and
Bermudagrass at 2.5 cm. Tissue samples were then oven dried
at 70°C for 48 hours to calculate weekly dry weight yields. The quality of the turf growing in each lysimeter was visually assessed bi-weekly. Turf quality assessment included percent cover and turf color. Turf cover was estimated on a percentage scale with 100% corresponding to total plant cover and 0% corresponding to bare soil. Turf color was based on a 1 to 10 scale with 1 as dead, brown grass and 10 as best. Turf canopy temperatures were measured at solar noon using an infrared thermometer (Everest Interscience, Tustin, CA).

Soil cores were collected from each lysimeter at the end of the 68 day drydown experiment. The cores were taken to a depth of 100 cm in 20 cm intervals. Soil samples were used to obtain a saturation extract (U.S. Salinity Laboratory Staff 1954). Extracts were analyzed for salinity (ECₐ) using an electrical conductivity bridge (Beckman Industrial Conductivity Bridge, Model R-20). ECₐ values were depth weighted to obtain a single value for each lysimeter.

Data were analyzed using linear and multiple linear regression analysis. Multiple regressions were performed in a backward stepwise manner with deletion of terms occurring when P values for the T test exceeded 0.05 (Anderson-Bell, 1986).
Results

Only results from the second year line source gradient study are reported, as first year results were highly mixed due to large variations in the distribution of salts relative to steady state conditions. Irrigation applications were highly linear with distance from the line source. Differences in irrigation applications were non-significant between water quality treatments (saline: $Y=5.71+4.57X$, $r=0.99***$, Fresh: $Y=3.84+4.53X$, $r=0.99***$, where $Y$ is irrigation volume in cm and $X$ is distance from line source in m). Decreasing irrigation volumes with distance, led to decreasing relative yields for both grasses under both water quality treatments (figure 1). Highest yields were observed under fresh water treatments when irrigation volumes ($I$) relative to potential evapotranspiration ($ET_o$) were at or near 1.0. However, as $I$ to $ET_o$ ratios dropped below 1.0, steeper declining slopes were observed under the freshwater treatments. Freshwater relative yield-$I/ET_o$ lines intercepted saline relative yield-$I/ET_o$ lines at an $I/ET_o$ value of approximately 0.38 for bermudagrass and 0.80 for tall fescue.

The irrigation gradient led to a clear separation in depth weighted soil salinity values between water quality treatments and also with distance from the line source under the saline treatment (figure 2). Higher average ECe values measured in lysimeters growing tall fescue compared to
bermudagrass under saline irrigations were related to the fact that irrigations were set at maintaining a 0.25 LF for tall fescue which led to slightly higher LFs on bermudagrass because of lower ETa values (same irrigation line). Under non-water deficit conditions (lysimeters adjacent to line source, with a 0.25 LF imposed during drydown), the yield was well described by the Maas and Hoffman equation (1977) for both grasses under both water quality treatments (figure 3). However, as water deficits increased, the yield salinity curves deviated significantly from the Maas and Hoffman curves (figure 3).

Yield was highly correlated with actual evapotranspiration (ETa) (tall fescue, ETa=15.18+1.09 (Yield), r=0.92***, bermudagrass, ETa=13.74+0.95 (Yield), r=0.83***). Low yields were associated with low evapotranspiration values and high yields were associated with high evapotranspiration values, regardless of how the stress was imposed (high-low salinity in combination with high-low water availability). Relative ETa values as a function of the summation of the leaf to air temperature difference (ΔT) during the 68 day drydown also indicated a non-distinguishable stress response based on water quality treatment. Higher cumulative ΔT values were associated with lower relative ETa values in both grasses, with the same equation describing the response under conditions of both fresh and saline irrigation (figure 4).
Turf quality was assessed by evaluating both turf color and percent cover during the line source gradient period. Color was evaluated on living tissue within the percent cover area. As such, color and cover were highly correlated (bermudagrass, Color=6.63+0.0222*Cover, r=0.87***, tall fescue, Color=3.30+0.0573*Cover, r=0.83***). Tall fescue showed a greater range in color than bermudagrass during the 68 day drydown period (1 - 9.5 vs 6.5 - 9.5). Relative color remained high and unchanged (at or near 1.0) for both grasses when I/ETo values exceeded 1.0, but began to decrease when I/ETo values dropped below 0.80 for tall fescue and 0.65 for bermudagrass (figure 5). Below these I/ETo threshold values, relative turf color declined in a linear fashion, with clear separation based on water quality treatments with tall fescue but not with bermudagrass (figure 5). In the case of tall fescue, higher turf color ratings were associated with the saline treatment under water deficit conditions (low I/ETo values). Relative percent cover as a function of I/ETo also remained high and unchanged at high I/ETo values for both grasses. However, just as color declined beyond an I/ETo threshold value, so did percent cover (Figures 6). In the case of tall fescue, percent cover began to decline and separate based on the water quality treatment when I/ETo values dropped below 0.80, with higher percent cover values associated with the saline treatment. In bermudagrass, percent cover began to
decline when I/ETo values dropped below 0.60 with no separation based on water quality treatment (figure 6).

Multiple regression analysis (deleting terms that were not significant at the 0.05 probability level) revealed that a combination of the salinity of the irrigation water (ECi) and I/ETo accounted for 46% of the variability in color (Color=7.48–0.05ECi+1.52I/ETo, \( p=0.01 \)), 56% of the variability in % cover (Cover=34.3–0.42ECi+63.4I/ETo, \( p=0.01 \)) and 69% of the variability in yield (Yield=5.94–0.98ECi+24.20I/ETo, \( p=0.001 \)) of bermudagrass. In tall fescue, 47% of the variability in color (Color=0.02+0.35ECi+7.36I/ETo, \( p=0.01 \)), 70% of the variability in % cover (Cover=−50.2+4.68ECi+126.00I/ETo, \( p=0.001 \)) and 64% of the variability in yield (Yield=−5.77–0.19ECi+31.50I/ETo, \( p=0.001 \)) could be accounted for through the combination of ECi and I/ETo values.

Discussion

It has been well established that plant growth declines in response to water deficit conditions (Bittman and Simpson 1987, Jones 1992). Plant growth has also been shown to be further depressed when the root zone is subjected to the combination of an osmotic and a matric induced stress (Hoffman et al. 1983, Devitt et al. 1993). Results from this study suggest that the physiological response of both bermudagrass and tall fescue is driven by the increasing
water deficit conditions (with increasing distance from the line source). No separation in AT values based on water quality treatments were observed, suggesting that within the range of matric (I/ET₀) and osmotic (ECₑ) combinations established in our study, plants integrated stress (water and/or salt) in a similar fashion. Childs and Hanks (1975) in developing a model for soil salinity effects on crop growth, also considered the effects of a matric and osmotic potential to be identical on plant growth and transpiration.

Both grasses showed steeper declines in yield in response to drying when irrigated with fresh water than when irrigated with saline water. The fresh treatment for both grasses had higher yields than the saline treatment at an I/ET₀ of 1.0. However, plants growing in the fresh treatment showed a lower capacity to adjust to the extreme water deficit conditions established in the lysimeters farthest from the line source (Figure 1).

Soil salinity values were two to three times higher in the saline treatment than in the fresh treatment (Figure 2), yet at low I/ET₀ values higher relative yields were measured or estimated under saline conditions based on yield-I/ET₀ curves. We interpret this response to indicate that bermudagrass and tall fescue growing under lower salt conditions expended less energy extracting available soil water, leading to a faster and greater exploitation of the available soil water. Similar results have been reported by
Devitt et al. (1993) for bermudagrass during an extended drydown period under a range of soil salinity. In this experiment, ratios of water in storage to initial water in storage in the farthest lysimeters on the gradient over the 68 day dry down period, revealed values dropping below 0.70 by week 2 in tall fescue under fresh irrigation compared to week 4 under saline irrigation. In the most severely droughted lysimeters (13 m from the line source) of bermudagrass, the water in storage fell below 0.70 by week 5 under fresh irrigation compared to week 7 under saline irrigation. This accelerated storage depletion in the most distant lysimeters from the line source (especially when irrigated with fresh water), contributed significantly to the decline in turf color, % cover and overall growth of both turfgrasses (see figures 1, 5, and 6).

Water deficit conditions can exacerbate the stress placed on plants growing under saline conditions. Deviations in relative yield from the Maas and Hoffman (1977) equations indicate that the successful use of saline waters for irrigation purposes will be linked to irrigation management that eliminates soil moisture deficit conditions (United States Salinity Lab Staff 1954, Shalhevet 1984, Bresler et al. 1982). Bermudagrass has been described as a highly salt tolerant species (Marcum and Murdoch 1990, Dudeck and Peacock 1985, Maas and Hoffman 1977, Devitt 1989). Bermudagrass is also a very drought tolerant
species, with no loss in % cover or color until I/ETo values dropped below 0.65. Similar results were reported by Gibeault et al. (1985) under non-saline conditions. Tall fescue, however, was only moderately drought tolerant as both % cover and color declined quickly after I/ETo values dropped below 0.80, with yields under saline irrigation exceeding those obtained under fresh irrigation when I/ETo values dropped below 0.80. The results from this experiment support the selection of bermudagrass over tall fescue in arid climates where excess salt and water deficit induced stress present challenging growth environments for turfgrass.

Turfgrass growers/managers are interested in salinity/drought effects on turfgrass quality to a far greater extent than they are on the salinity/drought effects on turfgrass yield. This study demonstrated that both grasses can be successfully grown with acceptable turf quality using water that has a salinity level as high as 6.0 dSm$^{-1}$, if irrigation management practices maintain I/ETo ratios above the species specific threshold. However, certain caveats must be attached to such wastewater use programs before they are initiated on urban landscapes. These include; 1) the results reported herein should not be extrapolated to other turfgrass species or varieties, 2) results may vary from those reported, based on salinization period, soil type, and management input variables such as
fertilization rates and irrigation frequencies (Devitt et al. 1991), 3) the response on mixed landscapes can not be assessed based on this research, as foliar damage may be significant on trees (Ehlig and Bernstein 1959), 4) concentrations of Boron in the water may further restrict the usage of such waters on mixed landscapes (Francois and Clark 1979) and 5) utilization of such water requires the maintenance of high irrigation system uniformities and the ability to maintain tight ET feedback systems to achieve acceptable leaching fractions and salt balances (Devitt et al. 1992).
Table 1a. Ion concentration in the irrigation water and soil characteristics of research site

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<th>Water Characteristics</th>
<th>Well</th>
<th>Irrigation</th>
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<tr>
<td>EC (dS m⁻¹)</td>
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<td>B (mg kg⁻¹)</td>
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<table>
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<td>Organic Matter</td>
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Figure 1a. Site design and layout
Figure 2a. Relative yield (ratio of lysimeter yield to yield from fresh treatment lysimeters adjacent to irrigation source) of both grass species separated by irrigation treatment as a function of the ratio of total irrigation volume to total potential evapotranspiration for the 68 day dry down period, including standard error bars. (○ Yield=0.14+0.49(I/ET₀) r=0.79*, • Yield=-0.05+0.67(I/ET₀) r=0.92***, □ Yield=-0.03+0.94(I/ET₀) r=0.98***, ■ Yield=-0.82+1.64(I/ET₀) r=0.85**)
Figure 3a. Depth weighted soil salinity (ECe, dSm⁻¹) with distance from the irrigation line source by grass species and irrigation treatment, including standard error bars. (Bermudagrass-saline ○ ECe=8.95+0.36(Distance) r=0.84**, tall fescue-saline ● ECe=11.36+0.26(Distance) r=0.44, bermudagrass-fresh □ ECe=4.49+0.09(Distance) r=0.67*, tall fescue-fresh ■ ECe=4.94+0.02(Distance) r=0.18*)
Figure 4a. Relative yield (ratio of lysimeter yield to yield from fresh treatment lysimeters adjacent to irrigation source) as a function of soil salinity ($EC_e$, dSm$^{-1}$). The thick solid line is the response predicted for each grass under well watered conditions based on data from Maas and Hoffman (1977). (○ Rel yield = 1.52 - 0.09($EC_e$) $r = 0.90^*$, ● Rel yield = 1.51 - 0.10($EC_e$) $r = 0.90^*$, □ Rel yield = 0.96 - 0.29($EC_e$) $r = 0.34^{NS}$, ■ Rel yield = 3.00 - 0.49($EC_e$) $r = 0.24^{NS}$)
Figure 5a. Ratio of actual evapotranspiration measured in lysimeters to the maximum value measured in lysimeters from the fresh water treatment as a function of the difference between leaf temperature and ambient temperature taken at solar noon. (Bermudagrass: $\frac{ET_a}{ET_{max}} = 0.88 - 0.005 [\Delta (T_l - T_a)] \quad r=0.86^{**}$, Tall Fescue: $\frac{ET_a}{ET_{max}} = 0.75 - 0.003 [\Delta (T_l - T_a)] \quad r=0.94^{**}$)
Figure 6a. Relative turf color (final color rating on day 68 to initial color rating for lysimeters adjacent to the irrigation line under the fresh treatment) as a function of the I/ET$_0$ ratio for the 68 day experimental period, for each grass species by irrigation treatment, including standard error bars. The following equations represent the linear fit of the data below the species specific threshold. Combined fresh and saline bermudagrass data: Rel color = 0.75 - 0.39(I/ET$_0$) r=0.90***, Tall Fescue: Saline ○ Rel Color = 0.36 + 0.69(I/ET$_0$) r=0.75*, Fresh ■ Rel Color = -1.39 + 2.67(I/ET$_0$) r=0.91**
Figure 7a. Relative percent cover (final cover rating on day 68 to initial cover rating for lysimeters adjacent to the irrigation line under the fresh treatment) as a function of the I/ET₀ ratio for the 68 day experimental period, for each grass species by irrigation treatment, including standard error bars. At the experiment initiation, the percent cover for all lysimeters was at 100% (full coverage). Combined fresh and saline bermudagrass data: Rel % cover = -0.15+2.03(I/ET₀) r=0.93***, Tall Fescue: Saline ○ Rel % Cover = -0.23+1.38(I/ET₀) r=0.90**, Fresh ■ Rel % Cover = -1.98+3.20(I/ET₀) r=0.97***
CHAPTER 3

PHYSIOLOGICAL RESPONSE OF TWO TURFGRASS SPECIES TO VARYING RATIOS OF SOIL MATRIC AND OSMOTIC POTENTIALS

ABSTRACT

Plants grown under saline conditions can experience both elevated matric and osmotic stress during the time between irrigation events. Research was conducted to assess the physiological response of tall fescue (*Festuca arundinacea* Schreb 'Monarch') and an improved common bermudagrass (*Cynodon dactylon* L.'Numex Sahara') to varying ratios of soil matric ($\Psi_m$) and osmotic potentials ($\Psi_h$). Two line source gradient experiments were conducted, one used municipal water with an EC of 1.1 dSm$^{-1}$ and the other used saline aquifer water blended with municipal water to an EC of 6.0 dSm$^{-1}$. Turf temperature, leaf xylem water potential ($\Psi_t$), tissue osmolality ($\Psi_{n-TISS}$), yield, evapotranspiration ($ET_o$), percent cover, turf color, and tissue ion concentrations were monitored during a 68 day drydown period during the summer of the second year of experimentation. The total soil water potential was highly linear with
distance from the line source with no significant difference between fresh and saline treatments within each species (bermudagrass Adj $R^2=0.867^{***}$, tall fescue Adj $R^2=0.810^{***}$). Each treatment did show separation if each water potential component was considered independently with distance. Significantly lower soil osmotic potentials were recorded under the saline treatment, while lower soil matric potentials were recorded under the fresh treatment for both species. Turf temperature, yield, $ET_a$, turf color, and canopy cover responded to $\Psi_T$ regardless of the ratio of $\Psi_M$ and $\Psi_N$. $\Psi_L$, $\Psi_N$-TISS and tissue ion concentrations in bermudagrass and $\Psi_L$, $\Psi_N$-TISS, stomatal conductance, and tissue ion concentrations in tall fescue responded in a synergistic fashion to $\Psi_M$ and $\Psi_N$. WUE (water use efficiency = total yield/total $ET_a$) remained fairly constant in bermudagrass with decreasing $\Psi_T$. Tall fescue, however, exhibited higher WUEs under lower stress conditions. Tissue ion concentrations (with the exception of $K^+$) increased only slightly in bermudagrass in response to increasing salinity. Whereas, tissue ion concentrations in tall fescue increased significantly to increasing salinity. Our results suggest that water with a salinity level of 6.0 dS$m^{-1}$ could be used as a supplemental irrigation source for both tall fescue and bermudagrass if irrigation practices were designed to minimize water deficit conditions.
Introduction

A large portion of the earth's land mass is located in arid regions. Growing plants in this region is a constant challenge to farmers/growers due to limited water resources and the presence of salts in both soils and irrigation waters. How plants growing in such environments respond to either drought stress or salt accumulation have been previously documented. Ludlow (1989) produced a fairly complete review paper on plant response to drought stress. Plant response to salinity has also been discussed in excellent papers over the years (Waisel 1991, Greenway and Munns 1980). However, most salinity studies have been done under well watered conditions to minimize any matric effects, while water deficit experiments typically have used waters with low soluble salt levels to minimize any osmotic effects.

Plants grown under field conditions must integrate stress associated with water availability and the presence of soluble salts simultaneously, especially when irrigation waters contain a significant salt load. This is often the case for irrigation waters in arid regions. Reclaimed sewage effluent (Hayes et al. 1990), blow down water (Jury et al. 1978), saline ground water (Dean et al. 1996), and saline drainage waters (Rhoades et al. 1989) have all been used or suggested as alternative irrigation sources for crops/plants in arid regions where good quality waters are
unavailable or too expensive. Because irrigations are cyclic in nature, this drives both matric and osmotic cycles, with the resulting level of stress developed dependent upon complex interactions within the soil-plant-atmospheric continuum. As greater demand is being placed on our available water resources, re-use of poor quality water will play an ever increasing role in the future. Use of poor quality water requires developing best management practices that will minimize the amount of stress plants experience. Therefore, knowledge of how plants integrate stress should be examined in order to not only get a clearer picture of the plants response to total water potentials but also to various matric-osmotic combinations that can result from irrigation practices.

The few studies that have investigated the physiological response of plants to total water potentials made up of varying matric and osmotic components have been done on crop species. Matric and osmotic potentials were found to have an additive effect on yield of corn (Hanks et al. 1978, Stark and Jarrell 1980, Frenkel et al. 1990) and evapotranspiration (Hanks et al. 1978, Childs and Hanks 1975). The two components were also found to have additive effects on yield and nitrogen uptake of wheat (Broadbent et al. 1988) and on the yield of cotton and pepper (Shalhevet and Hsiao 1986).

The combined effects of matric and osmotic stress on
the physiological response of turfgrass, where total yield is of less concern, has not been resolved. Therefore, this study was conducted to evaluate the physiological response of two turfgrass species (tall fescue and common bermudagrass) to soil water potentials comprised of varying matric and osmotic components.

**Methods**

A two year study to investigate the potential use of a shallow saline aquifer as an alternative irrigation source was conducted at a research site in Las Vegas, Nevada. A line source water gradient experiment was carried out during the summer of the second year (sixty-eight days). Treatments consisted of decreasing irrigation volumes with increasing distance from the irrigation line source (Hanks et al. 1976). Two identical line source experiments were conducted at the same site, separated by a common buffer zone. One line source received municipal water for irrigation (electrical conductivity EC = 1.1 dS/m) while the other line source received well water from a perched saline aquifer (blended to an EC of 6.0 dS/m with municipal water). Description of ion concentrations in the irrigation waters are reported in Table 1. Each line source experiment was further divided into equal areas (northern and southern sections of field) containing either Festuca arundinacea Schreb. 'Monarch' (Tall Fescue) or Cynodon dactylon L.
'Numex Sahara' (common bermudagrass) which was over seeded with *Lolium perenne* L., varietal composition of 50% "Palmer", 50% "Prelude" (perennial ryegrass).

The irrigation system was comprised of six sprinkler lines spaced 13.4 m apart. Rotor pop-up sprinklers (Toro 700 series, Toro Corporation, Riverside, Ca.) were spaced 6.7 m apart on each line. All irrigations were applied at 0.41 MPa (60 psi) to give a wetted radius of approximately 13.4 m. During each summer of the study, the outer irrigation lines (fresh and saline) were disconnected, setting up a well defined line source gradient. The three lines on the west side of the field were used to irrigate saline water, while the three lines on the east side of the field were used to irrigate municipal water.

Lysimeters were used to quantify the evapotranspiration of the turfgrasses growing under the imposed treatments. The lysimeters (51 cm diameter, 120 cm length) were all filled with the same blended surface soil taken from the field site to reduce soil variation between lysimeters. The soil was a fine-silty, mixed, thermic typic haplosalid. The soil had a pH of 8.0 and an organic matter content of 0.6%. Eighteen lysimeters were located in each of the water treatments, with nine lysimeters located in each turfgrass by water treatment area. The lysimeters were situated at 1, 5, 9, and 13 m from the irrigation line, replicated twice. The ninth lysimeter per quadrant was placed at the 4.6 m
The lysimeters were equipped with two drainage extraction cups placed in the bottom of the lysimeters in 10 cm of diatomaceous earth. A metal access tube, located in the center of each lysimeter allowed a neutron probe to be lowered into the soil to estimate soil water content. At the 30 cm depth, each lysimeter was further equipped with a soil psychrometer, a tensiometer, and a small extraction cup. The psychrometers (Wescor Inc, model PST55-10, Logan, UT), were connected to a microvoltmeter (Wescor Inc, model HR-33T-R, Logan, UT), to estimate total water potential. The tensiometers (Soil Moisture Systems, model SW-010, Tucson, AZ) were used to estimate soil matric water potential. Monthly soil solution samples were collected from the small extraction cup with the application of a -0.0173 MPa vacuum. These samples were then analyzed with a vapor pressure osmometer (Wescor, model 5100C, Logan, UT) to estimate the osmotic potential of the soil solution at 30 cm.

The psychrometers lost accuracy with time. The lysimeters in which the tensiometers recorded near zero matric potentials were too wet for the psychrometers to function, while the psychrometers in the drier lysimeters lost accuracy near the end of the experiment. This decline in reliability of the psychrometers in the drier lysimeters was possibly due to salt accumulation in and around the stainless steel heads. The tensiometers were unable to
register matric potentials below -0.1 MPa. In the drier lysimeters the air entry value was exceeded within 10 days after the line source gradient was imposed. Therefore, matric potentials were derived from a moisture release curve produced by a commercial laboratory, where gravimetric water contents in soil samples collected at the end of the experiment were used to predict matric potentials. The osmotic potential was measured on a saturation extracts of soil samples taken in 20cm increments to 100cm within each lysimeter. The osmolality was multiplied by a correction factor which accounted for the dilution between the saturation extracts and the water content of the collected soil. The total water potential was assumed to be the summation of the matric and osmotic components measured.

Nitrogen (NH₄-NO₃) was applied to all turfgrass areas containing lysimeters at a rate of 48.9 Kg ha⁻¹ month⁻¹. Nitrogen applied to the saline part of the field was reduced to compensate for the background nitrogen level in the saline water.

Irrigation volumes were calculated from the equation \( I = \frac{ET_a}{1 - LF} \), where \( I \) is the total irrigation for the week, \( ET_a \) is the actual evapotranspiration of the previous week and \( LF \) is the leaching fraction (drainage volume/irrigation volume). Actual evapotranspiration was calculated by the hydrologic balance approach (\( ET_a = \) Irrigation volume - Drainage volume - change in storage).
Irrigations were applied four days per week. Irrigation volumes applied to each lysimeter were estimated after each irrigation by measuring the volume of water that was collected in a catchcan placed at the center of each lysimeter. Drainage volumes were collected from each lysimeter by applying a vacuum (-0.0173 MPa) for one hour, four days per week on the buried suction extraction cups. Soil water in storage was calculated by integrating estimated volumetric water contents over depth. Calculated irrigation volumes were applied to the whole plot at a rate to maintain a leaching fraction (LF) of 0.25 in the lysimeter closest to the irrigation line source. Since bermudagrass and tall fescue were located on the same line source, irrigations were based on maintaining the 0.25 LF on the tall fescue.

Total solar radiation, wind run, rainfall, daily minimum and maximum ambient temperatures, as well as daily minimum and maximum relative humidities were collected from an automated weather station (Campbell Scientific, Model 012, Logan, UT). Daily potential evapotranspiration ($ET_o$) was then calculated by inputing these parameters into the modified Penman Combination Equation (Campbell Scientific, Logan, UT).

Grass samples were harvested from each lysimeter on a weekly basis. Tall fescue was cut at 5.1 cm and Bermudagrass at 2.5 cm. Approximately 1g of each harvest
was placed in a leaf press to collect expressed fluids from the tissue. A 10um sample of this fluid was analyzed with a vapor pressure osmometer (Wescor Inc, 5100C, Logan, UT) to estimate tissue osmolality. The remaining tissue samples were then oven dried at 70°C for 48 hours to calculate weekly dry weight yields. The dried tissue samples were ground to a fine powder and digested for 20 minutes in 25 ml 0.5N nitric acid under a vacuum and then filtered. The collected extracts were analyzed for calcium, potassium, magnesium, and sodium with an atomic absorption spectrophotometer (Buck Scientific, model 200-A, E. Norwalk, CT). Chloride was measured with a chloride specific ion probe attached to a pH meter (Fisher, model 810, Santa Clara, CA). Sulfate concentration was estimated with a spectrophotometer (Shimadzu, model UV-120-02, Kyoto, Japan).

The quality of the turf growing in each lysimeter was visually assessed bi-weekly. Turf quality assessment included percent cover and turf color. Turf cover was estimated on a percentage scale with 100% corresponding to total plant cover and 0% corresponding to bare soil. Turf color was based on a 1 to 10 scale with 1 as dead, brown grass and 10 as best. Turf canopy temperatures were measured at solar noon using an infrared thermometer (Everest Interscience, Tustin, CA). Stomatal conductance (tall fescue) and leaf xylem water potential were also measured at solar noon with a porometer (LI-1600, Li-
Cor, Lincoln, Ne) and a pressure chamber (Soil Moisture Corp., Santa Barbara, Ca) respectively.

Soil cores were collected from each lysimeter at the end of the 68 day drydown experiment. The cores were taken to a depth of 100 cm in 20 cm intervals. One set of soil samples were used to measure the volumetric water content and the other set was used to obtain a saturation extract (U.S. Salinity Laboratory Staff 1954). Extracts were analyzed for salinity ($E_{c}$) using an electrical conductivity bridge (Beckman Industrial Conductivity Bridge, Model R-20) and for osmolality using a vapor pressure osmometer (Wescor, model 5100c, Logan, UT). $E_{c}$ and osmolality values were depth weighted to obtain a single value for each lysimeter.

Data were analyzed using linear and multiple linear regression analysis. Multiple regressions were performed in a backward stepwise manner with deletion of terms occurring when P values for the T test exceeded 0.05 (Anderson-Bell, 1986).

**Results**

The field site was salinized for 18 months prior to the second year line source gradient study. This initial period was necessary for complete profile salinization, such that a clear and discernable osmotic effect would be present.

The psychrometers used to measure total water potentials ($\Psi_t$) lost accuracy with time in both the outside
drier lysimeters and inside wetter lysimeters. The relationship between the psychrometric $\Psi_t$ measured at 30cm and $\Psi_t$ derived from the gravimetric and soil solution samples collected at 30cm were highly linear ($R^2=0.689$, $p<0.001$). However, in the inside lysimeters, the soils were too wet for the psychrometers to function. In the outside drier lysimeters where the same psychrometers were maintained for more than 30 days, water potentials substantially deviated from the curve and under estimated $\Psi_t$ (i.e. measured -1.5MPa when estimated total water potential was closer to -3.0 MPa). Because of this discrepancy in water potential measurements in the drier lysimeters, the lack of response in the wetter lysimeters, and because single depth measurements at 30cm did not always correlate with plant response, we chose not to use psychrometric estimates of $\Psi_t$. Instead total water potentials reported are the summation of the gravimetrically derived matric ($\Psi_m$) and the adjusted soil extract osmotic ($\Psi_n$) water potentials averaged over the 0 to 100 cm soil depth.

All treatments received approximately the same irrigation for the 68 day drydown experiment, with linearly decreasing irrigation volumes with distance (Figure 1). The $\Psi_t$ was also highly linear with distance from the line source with no significant difference between fresh and saline treatments within each grass species (Ber $\Psi_t=-0.143-0.159$ (distance) Adj $R^2=0.867^{***}$, Pes $\Psi_t=-0.304-0.210$ (distance))
Adj $R^2=0.810^{***}$). Each treatment did show separation if each water potential component was considered independently with distance. Significantly lower $\Psi_n$ were recorded in lysimeters growing both tall fescue and bermudagrass under saline irrigation (Figure 2). However, lower matric potentials were measured in lysimeters growing both grass species under fresh irrigation (Figure 2).

Irrigations were scheduled to produce a 0.15 leaching fraction on tall fescue. Since both grasses were grown under the same line source gradient and the ET of bermudagrass was lower than that measured for tall fescue, the same irrigation volume led to a higher leaching fraction on the bermudagrass. Therefore, the tall fescue experienced a greater range in the level of stress imposed than did the bermudagrass. Total soil water potentials in bermudagrass ranged from -0.43 to -2.50 MPa while total soil water potentials in tall fescue ranged from approximately -0.50 to -3.79 MPa.

The sum of the difference between the leaf temperature and ambient temperature ($\Sigma \Delta T$) increased as $\Psi_t$ decreased (bermudagrass $\Sigma \Delta T=-34.7 - (64.4*\Psi_t)$, Adj $R^2=0.891^{***}$, tall fescue $\Sigma \Delta T=-79.3 - (71.1*\Psi_t)$, Adj $R^2=0.717^{***}$). In bermudagrass, $\Psi_t$ accounted for 89.1% of the variability in $\Sigma \Delta T$, while ($\Psi_H, \Psi_n$) accounted for 91% of the variability in $\Sigma \Delta T$ (Table 2). However, $\Sigma \Delta T$ when regressed against matric potentials alone explained 66.1% of the variability of the
data while the osmotic potentials alone were non-significant in explaining changes in ΣΔT.

Tall fescue's ΣΔT was also correlated to Ψᵣ regardless of the ratio of Ψₘ to Ψₚ (Table 2). The matric and osmotic components contributed to the stress response of tall fescue on a more equal basis than was observed in bermudagrass (Adj R²-matric=0.485**, Adj R²-osmotic=0.375**).

Total dry yield was negatively affected by increasing water stress (bermudagrass yield=34.3+(11.8*Ψᵣ) Adj R²=0.678***, tall fescue yield=35.9+(10.4*Ψᵣ), Adj R²=0.761***). Yield responded to Ψᵣ without regard to the ratio of Ψₘ to Ψₚ for both bermudagrass and tall fescue. The variability explained by Ψᵣ or (Ψₘ,Ψₚ) vs yield were not significantly different.

Actual evapotranspiration (ETₐ) decreased significantly as Ψᵣ became more negative (bermudagrass Total ETₐ=50.7+(14.7*Ψᵣ), Adj R²=0.845***, tall fescue Total ETₐ=55.6+(12.1*Ψᵣ), Adj R²=0.727***). Total ETₐ showed the same decreasing trend as yield did for both grass species. An average of 78.6% of the ETₐ variability was explained by Ψᵣ, while an average of 77.1% of the variability was explained if the potential components were separated. Again, neither the matric nor osmotic potential appeared to be the overriding component in defining ETₐ.

Although good correlations were found between both yield and ETₐ with Ψᵣ, WUE of bermudagrass exhibited no
significant changes in response to changes in water stress imposed (Table 2). Tall fescue, on the other hand, had larger WUEs with decreasing stress (tall fescue WUE=0.771+(0.160*Ψₙ)+(0.107*Ψₘ), Adj $R^2=0.757^{***}$) (Figure 3). Specifically, tall fescue responded to the water potentials, in an additive way. Although tall fescue expended more water per gram of dry yield, as either the water deficit or salt stress increased, the response was more osmotic driven (Adj $R^2=0.629^{***}$) than matric driven (Adj $R^2=0.284$).

Both aesthetic parameters (% cover and turf color) decreased as $Ψₜ$ became more negative (bermudagrass %cover=115.5+(29.9*$Ψₜ$), Adj $R^2=0.800^{***}$, color=9.17+(0.644*$Ψₜ$), Adj $R^2=0.837^{***}$, tall fescue %cover=116.7+(24.7*$Ψₜ$), Adj $R^2=0.700^{***}$, color=9.67+(1.00*$Ψₜ$), Adj $R^2=0.766^{***}$). These parameters also responded to $Ψₚ$ and $Ψₙ$ stress in an additive not synergistic way. Slightly better correlations were found with bermudagrass than tall fescue but the trends were very similar.

Stomatal conductance data was collected only for tall fescue. Stomatal conductances ($C_s$) decreased with decreasing $Ψₜ$ (Tall fescue $C_s=1.48+(0.314*Ψₜ)$, Adj $R^2=0.675^{***}$). $Ψₚ$ and $Ψₙ$ potentials may have had a slight synergistic effect on $C_s$ (Adj $R^2(Ψₚ,Ψₙ)=0.751^{***}$, Adj-$R^2(Ψₜ)=0.675^{***}$) with the $C_s$ response driven more by the soil osmotic potential (Adj $R^2=0.666^{***}$) than the matric potential (Adj $R^2=0.226^{NS}$).
A synergistic interaction of Ψ_m and Ψ_n was observed with leaf xylem water potential (Ψ_L) and tissue osmolality (Ψ_n-TESS) in bermudagrass (Table 2). Both parameters were driven more by the soil osmotic potentials. Although the correlation with matric potentials alone was insignificant, a clear synergistic effect was observed between Ψ_m and Ψ_n. The Ψ_n-TESS for tall fescue also showed a synergistic response to Ψ_m and Ψ_n, while Ψ_L did not. The Ψ_L of tall fescue was driven by the soil osmotic potential, with no greater account of the variability when Ψ_m and Ψ_n components were individually considered.

Tissue ion concentrations in all cases where statistical significance was observed was regulated by the osmotic potential of the soil, with a superior response to Ψ_T if the components were both considered (Table 3). In bermudagrass, only K⁺ and Na⁺ showed significant correlations with Ψ_T. The tissue K⁺ concentration significantly decreased with decreasing soil osmotic potential (\( \%K = 2.47 + (0.48*Ψ_n) \), Adj R² = 0.513^∗). The soil Ψ_m appeared to have no effect on the K⁺ concentration in the tissue and in fact decreased the R² value when it was considered in the correlation. Na⁺ tissue concentrations, on the other hand, showed no correlation with Ψ_m or Ψ_n components when considered separately. However, if Ψ_m and Ψ_n were considered together, 35.8% of the variability in the Na⁺ tissue concentration could be accounted for through a
regression model. The tissue Na' concentration increased as $\Psi_T$ became more negative in bermudagrass.

In tall fescue, all ions, except K', increased in the tissue as $\Psi_h$ became more negative (Table 3). When $\Psi_h$ and $\Psi_m$ potentials were considered separately, no significant correlations were observed between tissue ion concentrations and matric potentials. In all cases except K', considering both components separately in the total water potential estimate was superior to considering them in an additive way.

**Discussion**

In this study we have demonstrated the usefulness of the line source gradient technique in differentiating turfgrass species response to both matric and osmotic stress. Total irrigation volumes were shown to decrease with distance from the irrigation source creating a water deficit gradient (Hanks et al. 1980, Novero et al. 1985, Barragon and Recasens 1988). Of greater significance, however, was the fact that lower soil matric potentials were measured under fresh water irrigation. These results would suggest that both bermudagrass and tall fescue exploited available water to a greater extent under non-saline conditions which placed the plants under greater stress during a prolonged drydown period. This trend was also found in wheat and barley (Hao and de Jong 1988), cotton and
pepper (Shalhevet and Hsiao 1986), and bermudagrass (Devitt et al. 1993).

The two species studied differed in their water use, with tall fescue using up to 18% more water than bermudagrass under non-stressed conditions. Cool season grasses, like tall fescue, have been found to transpire up to 40% more water than corresponding warm season species, like bermudagrass (Biren et al. 1981).

Few studies have tried to assess the physiological response of plants to water stress by separating $\Psi_T$ into $\Psi_M$ and $\Psi_n$ components (Sepaskhah and Boersma 1979, Parra and Cruz-Romero 1980, Jensen 1982, Shalhevet and Hsiao 1986, Hao and de Jong 1988, and Devitt et al. 1993). Within the range of $\Psi_T$ experienced in this study, yield, evapotranspiration, canopy cover, and turf color responded to $\Psi_T$ regardless of the ratio of $\Psi_M$ and $\Psi_n$. Jensen (1982) also concluded that the response of yield and evapotranspiration of barley were due to the additive effects of $\Psi_M$ and $\Psi_n$. However, the yield of beans (Phaseolus vulgaris) (Parra and Cruz-Romero 1980), the growth of wheat seedlings (Sepaskhah and Boersma 1979), and the evapotranspiration, assimilation, and growth of cotton (Gossypium girsutum) and pepper (Capsicum annuum) (Shalhevet and Hsiao 1986) were found to respond more strongly to changes in $\Psi_M$ than $\Psi_n$, suggesting that the response was not simply additive. Hao and de Jong (1988) found that the
growth of wheat and barley seedlings responded additively to $\psi_m$ and $\psi_n$ until the stress reached a species specific tolerance level, then $\psi_m$ had a greater effect.

$\psi_l$ and $\psi_{n-tiss}$ in bermudagrass and $\psi_l$, $\psi_{n-tiss}$, and stomatal conductance did respond in a synergistic fashion to $\psi_m$ and $\psi_n$. In all cases, $\psi_n$ was better correlated to these parameters than was $\psi_m$. $\psi_m$ typically showed non-significant correlations. However, the combination of the two parameters in a multiple regression model was superior to the $\psi_l$ correlation. The synergistic effect may have been due to both cellular dehydration and increased ion uptake occurring simultaneously under saline conditions.

WUE remained fairly constant in bermudagrass with decreasing $\psi_l$. Tall fescue, on the other hand, exhibited higher WUEs when grown under low stress conditions than when grown under higher stress conditions. Garrity et al. (1982) found the trend in WUE of sorghum with water stress to be predominantly negative. Turk and Hall (1980) reported the WUE of soybean to improve by moderate soil water deficits, especially during the vegetative stage. Whereas, Green and Read (1983) reported increased WUE for both corn and sunflower under limited moisture conditions. We believe the C$_4$ photosynthetic pathway of bermudagrass enabled it to maintain a fairly constant rate of photosynthesis relative to transpiration. Tall fescue, a C$_3$ grass, demonstrated an enhanced photosynthetic capacity under low stress conditions.
with a higher yield to water use rate. However as the stress increased, tall fescue reduced water loss at a rate slower than that observed for new tissue production.

Bermudagrass was able to regulate ion accumulation in the aboveground tissue better than tall fescue. Tissue ion concentrations, except $K^+$, rose only slightly in response to increasing salinity. Similar results were reported by Ackerson and Younger (1975). Further, the $\Psi_L$ and $\Psi_{n-tiss}$ decreased less in bermudagrass than in tall fescue under increased salinity. Common bermudagrass has been reported by many investigators to be a salt tolerant grass (Ackerson and Younger 1975, Maas and Hoffman 1977, Marcum and Murdock 1990, Devitt et al. 1991). Francois (1988) found that two different bermudagrass cultivars 'Tifton II' and Tifton 86 were unaffected by ECe's below 8.4 and 10.4 dS m$^{-1}$ respectively, under well watered conditions. The ECe, for bermudagrass, in our experiment averaged 11.2 dS m$^{-1}$ for the saline treatment and 5.1 dS m$^{-1}$ for the fresh treatment. A 20% yield loss in bermudagrass grown under saline conditions was observed when moisture deficits were avoided, indicating that the tolerance limit had been exceeded. However, these conditions produced no change in turf quality (Dean et al. 1996).

Lower salinity threshold values have been reported for tall fescue (Maas and Hoffman 1977). In our experiment, tall fescue was not able to restrict the uptake of ions as
well as bermudagrass (Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), Cl\(^-\), and SO\(_4\)\(^{2-}\) tissue concentrations all significantly rose with increased salinity). D. Bowman (personal communication, 1995) found similar trends in tall fescue when the grass was irrigated with saline water up to 120 meq/l with a Na\(^+\)-Ca\(^{2+}\)-Cl\(^-\) solution. Marcum and Murdoch (1990) found that bermudagrass maintained low levels of Na and Cl in both roots and shoots under high salinity, which they stated was an indication of ion regulation, due in part to efficient leaf salt glands. Although, ion accumulation in tall fescue may have provided some initial benefit to the plant in the maintenance of cellular turgor through osmotic adjustment, continued uptake may have reached toxic levels where normal cellular processes, like photosynthesis or protein synthesis, were disrupted (Downton et al. 1985, Cramer et al. 1990).

Saline waters have been shown to cause no detrimental response in plants if irrigation practices are designed to minimize \(\Psi_m\) driven \(\Psi_m\) oscillations beyond species specific salinity thresholds (Gratten et al. 1987, Hoffman et al. 1983). Management decisions may include irrigating with saline water during more salt tolerant growth stages, seasonal or annual cycling of fresh and saline irrigations, or blending saline water with non-saline water to maintain salinity levels within tolerance limits (Bradford and Letey 1992).

Our results would suggest that water with a salinity
level of 6.0 dSm⁻¹ could be used as a supplemental irrigation source for both tall fescue and bermudagrass. However, comparing the effect of a unit change (1.0 MPa) in matric vs osmotic potential, a 20 to 35% greater decrease in yield, ET, and cover was observed under the unit decrease in matric stress for both grasses. Irrigation management of turfgrass associated with the utilization of waters containing appreciable levels of soluble salts must therefore be based on minimizing matric stress if best results are to be achieved.
Table 1b. Saline Irrigation and Municipal Irrigation Water characteristics

<table>
<thead>
<tr>
<th>Water Characteristics</th>
<th>Irrigation</th>
<th>Municipal</th>
</tr>
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<tbody>
<tr>
<td>EC (dSM⁻¹)</td>
<td>5.95</td>
<td>1.08</td>
</tr>
<tr>
<td>Na⁺ (mmolL⁻¹)</td>
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<td>4.61</td>
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<tr>
<td>K⁺ (mmolL⁻¹)</td>
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<td>Ca²⁺ (mmolL⁻¹)</td>
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<td>Mg²⁺ (mmolL⁻¹)</td>
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<td>Cl⁻ (mmolL⁻¹)</td>
<td>16.12</td>
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<td>HCO₃⁻ (mmolL⁻¹)</td>
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<td>CO₃⁻ (mmolL⁻¹)</td>
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<td>0.00</td>
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<td>NO₃⁻-N (mmolL⁻¹)</td>
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<td>Adj-SAR</td>
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<tr>
<td>B (mgKg⁻¹)</td>
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Table 2b. Adjusted R² of correlations between plant physiological responses to $\Psi_M$, $\Psi_n$, $\Psi_t$, and a multiple regression with $\Psi_M$ and $\Psi_n$. $\Psi_t$ is the summation of $\Psi_M$ and $\Psi_n$. NS=non-significant, *, **, ***, represent p values of 0.05, 0.01, 0.001 respectively.

<table>
<thead>
<tr>
<th></th>
<th>$\Psi_M$</th>
<th>$\Psi_n$</th>
<th>$\Psi_t$</th>
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<tr>
<td><strong>BERMUDAGRASS</strong></td>
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<td></td>
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<tr>
<td>$\Sigma(T_1-T_n)$</td>
<td>66.1***</td>
<td>22.2NS</td>
<td>89.1***</td>
<td>91.0***</td>
</tr>
<tr>
<td>$\times\Psi_L$</td>
<td>8.1NS</td>
<td>61.0***</td>
<td>59.8***</td>
<td>71.6***</td>
</tr>
<tr>
<td>$\times$ TIS OSM</td>
<td>0.8NS</td>
<td>76.2***</td>
<td>55.8***</td>
<td>80.7***</td>
</tr>
<tr>
<td>$\Sigma$ YIELD</td>
<td>38.1**</td>
<td>25.8*</td>
<td>67.8***</td>
<td>65.3***</td>
</tr>
<tr>
<td>$\Sigma$ ET_a</td>
<td>41.9**</td>
<td>35.5*</td>
<td>84.5***</td>
<td>83.4***</td>
</tr>
<tr>
<td>$\times$ % COVER</td>
<td>40.9**</td>
<td>36.0*</td>
<td>80.0***</td>
<td>78.6***</td>
</tr>
<tr>
<td>$\times$ COLOR</td>
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<td>40.1**</td>
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<td>82.9***</td>
</tr>
<tr>
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<td>-7.0NS</td>
<td>8.6NS</td>
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<tr>
<td><strong>TALL FESCUE</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Sigma(T_1-T_n)$</td>
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<td>37.5**</td>
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</tr>
<tr>
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<tr>
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<tr>
<td>$\Sigma$ ET_a</td>
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<td>42.2&quot;</td>
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<tr>
<td>$\times$ % COVER</td>
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<td>WUE</td>
<td>28.4&quot;</td>
<td>62.9***</td>
<td>71.2***</td>
<td>75.7***</td>
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Table 3b. Adjusted $R^2$ of correlations between plant tissue ion concentrations and $\Psi_M$, $\Psi_n$, $\Psi_T$, and a multiple correlation with $\Psi_M$ and $\Psi_n$. $\Psi_T$ is the summation of $\Psi_M$ and $\Psi_n$. NS=non-significant, *, **, ***, represent p values of 0.05, 0.01, 0.001 respectively.

<table>
<thead>
<tr>
<th></th>
<th>$\Psi_M$</th>
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<th>$\Psi_T$</th>
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<td><strong>BERMUDAGRASS</strong></td>
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<td>$%$ CALCIUM</td>
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<td>$6.5^{NS}$</td>
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<td>$3.2^{NS}$</td>
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<td>$13.0^{NS}$</td>
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<tr>
<td><strong>TALL FESCUE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$%$ CALCIUM</td>
<td>$-5.8^{NS}$</td>
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<td>$66.3^{***}$</td>
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<td>$%$ SODIUM</td>
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<td>$53.9^{***}$</td>
<td>$4.2^{NS}$</td>
<td>$67.9^{***}$</td>
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<td>$%$ CHLORIDE</td>
<td>$-3.7^{NS}$</td>
<td>$77.3^{***}$</td>
<td>$36.0^{**}$</td>
<td>$76.1^{***}$</td>
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<td>$%$ SULFATE</td>
<td>$7.2^{NS}$</td>
<td>$6.7^{NS}$</td>
<td>$-7.0^{NS}$</td>
<td>$26.4^{**}$</td>
</tr>
</tbody>
</table>
Figure 1b. Total irrigation volume (cm) as a function of distance (m) from the line source gradient. Data represents the combination of both turfgrass species for each water treatment.
Figure 2b. Soil matric and osmotic potentials as a function of distance from the irrigation line source. (a c = bermudagrass, b d = tall fescue, □ ■ = saline treatment, ○ □ = fresh treatment). Matric equations—bermudagrass:saline $Y=0.105-0.034X$ ADJ $R^2=0.66^{**}$, bermudagrass:fresh $Y=0.32-0.136X$ ADJ $R^2=0.76^{*}$, fescue:saline $Y=0.247-0.010X$ ADJ $R^2=0.79^{*}$, fescue:fresh $Y=0.232-0.151X$ ADJ $R^2=0.69^{*}$, Osmotic equations—bermudagrass:saline $Y=-0.350-0.116X$ ADJ $R^2=0.94^{***}$, bermudagrass:fresh $Y=-0.369-0.032X$ ADJ $R^2=0.72^{**}$, fescue:saline $Y=-0.672-0.121X$ ADJ $R^2=0.78^{**}$, fescue:fresh $Y=-0.415-0.052X$ ADJ $R^2=0.68^{*}$. Positions 1m and 5m for bermudagrass saline have been offset to show points.
Figure 3b. Water use efficiency for tall fescue as a function of declining soil matric and osmotic potentials.
CHAPTER 4

SUMMARY

The use of non-potable waters should be considered as alternative irrigation sources in areas where water supplies are limited. In this experiment, a perched saline aquifer located beneath the Las Vegas valley was blended with municipal water to an EC of 6.0 dSm$^{-1}$ and used to irrigate turfgrass. No adverse physiological responses in two turfgrass species occurred when oscillations in soil matric potentials ($\Psi_m$) were minimized. These results would suggest that the saline aquifer could be safely used as a supplemental irrigation source for tall fescue and bermudagrass if water deficit conditions were avoided.

Turf yield decreased with decreasing total soil water potential ($\Psi_t$) regardless if the stress was induced by $\Psi_m$ or $\Psi_n$. However, total yield is of less importance to turfgrass growers than is the aesthetic quality of the turf (turf color and canopy cover). No change in turf quality occurred in this experiment if the ratio of irrigation volume to potential evapotranspiration ($I/ET_0$) was maintained above 0.80 for tall fescue and 0.65 for bermudagrass.

Turf temperature and $ET_a$ also responded to $\Psi_m$ and $\Psi_n$ additively in both grasses. This may suggest that a
generalized stress response system exists to combat a variety of environmental stresses. However, $\Psi_L$, $\Psi_{R-TISS}$, and tissue ion concentrations in bermudagrass and $\Psi_L$, $\Psi_{R-TISS}$, $C_s$, and tissue ion concentrations in tall fescue responded to $\Psi_M$ and $\Psi_n$ synergistically. Each of these parameters had higher correlations with $\Psi_n$ than $\Psi_M$. The synergistic effect may have been due to both dehydration and increased ion uptake occurring simultaneously under saline and water deficit conditions.

In this study, a 1.0 MPa unit change in the soil matric potential had a 20 to 35% greater effect on yield, $ET_s$, and percent cover than an equal change in soil osmotic potential. It has been shown that salinity stress can enhance drought stress resistance (Jensen 1982, Stark and Jarrell 1980, Devitt et al. 1993). Increased soil ion concentrations under the saline treatment contributed to such a condition in this experiment. Water extraction rates under the saline treatment were reduced (as expressed by the higher $\Psi_M$ values under the saline treatment). Water uptake was reduced, resulting in a greater amount of water remaining available under a progressive drought. Increased tissue ion concentrations under saline irrigations possibly contributed to the maintenance of cellular turgor at lower soil $\Psi_t$ than was observed under fresh irrigations. Such results would suggest that potentially more water savings could be realized with the reduction of the total irrigation
volumes needed to meet the turf's transpirational demand under saline irrigation than fresh water irrigation.

A substantial amount of potable water could be saved if non-potable water were used for turfgrass irrigation. Further, knowledge of the specific water requirements of plants through time would aid in the design of irrigation management programs that would maintain acceptable plant stands and soil quality (chemical and physical properties). Future research should also assess the salinity/drought effects on other turfgrass species common to the arid southwest.

Finally, a large scale turfgrass irrigation project utilizing water from the perched saline aquifer should be implemented using this and other data to design the best irrigation management plan. Such a plan should meet the species' water demand while maintaining turfgrass quality, leaching fractions, and salt balances while minimizing fluctuations in $\Psi_m$. The irrigation plan could include cyclic irrigations. This would involve alternating weekly irrigations between low salinity and high salinity waters. Future research could focus on determining an appropriate cyclic irrigation schedule (i.e. 1:3 vs 2:5 saline/non-saline weekly irrigations) for tall fescue and bermudagrass that would maintain tolerable soil salinity levels without leading to any appreciable decline in turf quality.
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