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RESPONSE OF TALL FESCUE TO SALINE WATER AS INFLUENCED BY LEACHING FRACTIONS AND IRRIGATION UNIFORMITY DISTRIBUTIONS

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ABSTRACT

Response of Tall Fescue to Saline Water as Influenced by Leaching Fractions and Irrigation Uniformity Distributions

by

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Research was conducted to determine the impact leaching fractions (LF = drainage volume divided by irrigation volume) and irrigation uniformity distributions have on the response of tall fescue to irrigation with saline water. Tall fescue (Festuca arundinacea Schreb. 'Monarch') was grown in 18 plots, each with a centrally located lysimeter that enabled estimates of evapotranspiration and irrigation requirements. Imposed treatments included setting LFs at 0.05, 0.15. or 0.25 and manipulating plot irrigation systems such that Christiansen Uniformity Coefficients (CUC) were set at 0.65, 0.75, or 0.85. Saline irrigation water (2.5 dS m^{-1}) was applied for an 18-month period. Significant LF x CUC interactions were observed for depth-weighted soil salinity, yield, ET, tissue moisture content and canopy temperatures. Results suggest that plant response can be maintained when the LF is lowered, within limits, if the CUC is kept high.

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LIST OF ABBREVIATIONS

C_d	Concentration of salts in drainage
C_i	Concentration of salts in irrigation
CUC	Christiansen Uniformity Coefficient
CV	Coefficient of variation
D	Drainage volume
df	Degrees of freedom
EC_d	Electrical conductivity of drainage water
EC_e	Electrical conductivity of soil saturation extract
EC_i	Electrical conductivity of irrigation water
ET_a	Actual evapotranspiration
ET_o	Potential evapotranspiration
I	Irrigation volume
LF	Leaching Fraction
T_a	Ambient temperature
T_c	Canopy temperature
V_d	Drainage volume
V_i	Irrigation volume
ΔS	Change of water storage in root zone

θ_g	Soil gravimetric water content
*	Significance level of 0.05
**	Significance level of 0.01
***	Significance level of 0.001

GLOSSARY

Clothesline effect. The horizontal heat transfer from a warm upwind area to a relatively cooler crop field resulting in increased evapotranspiration, particularly at the field border.

Evapotranspiration. The combined processes by which water is transferred from the earth surface to the atmosphere; evaporation of liquid or solid water plus transpiration from plants.

Factor. A variable which may affect the dependent variable (i.e. the response). In this experiment, the dominant factors were meant to be (1) the leaching fraction and (2) the uniformity distribution.

Levels. The different values of a factor (e.g. for the leaching fraction, they are 0.05, 0.15 and 0.25).

Matric potential. The part of the total soil water potential that is due to the effects of the soil matrix. It may be defined as the energy per volume required to move from the reference state to the soil at the same elevation without adding solutes or changing pressure, temperature or allowing the soil above the point to exert a force.

Oasis effect. The vertical energy transfer from air to the crop; the effect of dry fallow surroundings on the microclimate of a relatively small area of land where an air mass moving into an irrigated area will give up much sensible heat. For small fields this may result in a higher evapotranspiration as compared to predicted evapotranspiration using climatic data collected inside the irrigated area. Conversely, evapotranspiration predictions based on weather data collected outside the irrigated fields may over predict actual evapotranspiration losses.

Osmotic potential. The part of the total soil water potential that is due to the presence of solutes in the soil water. It may be defined as the energy per volume required to move from the reference state to a solution identical in composition except for the addition of solutes.

Potential evapotranspiration. The rate at which water if available would be removed from wet soils and plant surfaces expressed as the rate of latent heat transfer per unit area or an equivalent depth of water.

Reclaimed water. Effluent from a wastewater treatment plant, which is put to any beneficial use.

Recycled water. Effluent from a satellite treatment plant, which is put to any beneficial utilization.

Reference state. A state having the following properties: (1) it is pure (i.e. without solutes), (2) it is free from external forces, (3) it is at the temperature and pressure of the vicinity soil, and (4) it has a defined reference elevation.

Response. Also called the dependent variable, it is the variable measured in the experiment. In this experiment, our interest was plant response. This response was reflected by various parameters such as canopy temperature and plant moisture content.

Satellite treatment plant. A treatment plant that generally is able to access cleaner effluent water than that received by a wastewater treatment plant (e.g. residential effluent) and which generally does not treat effluent waters to the same extent as a municipal wastewater treatment facility.

Salt tolerance. Salt tolerance is usually defined as the yield decrease expected for a given level of soluble salts in the root medium as compared with yields under non-saline conditions. It is usually described by a threshold EC value and a corresponding slope. Salt tolerance is a relative value since it also depends on water quality, type of plant, type of soil and environmental factors.

Soil water potential. The energy per unit quantity of water required to transfer water from the reference state to the state existing within the soil environment.

Transpiration. The rate of water loss from the plant through the formation of water vapor in living cells, which is regulated by physical and physiological processes.

Treatments. The different factor-level combinations used in an experiment (e.g. three different treatments may be 'LF = 0.05 and high CUC' or 'LF = 0.05 and low CUC' or 'LF = 0.25 and medium CUC'.

Turf cover. Plant volume per unit area.

Wetting front. A sharply defined region at the head of the infiltrating front where the suction and water content change from values characteristic of the wetted profile to those characteristic of the soil ahead of the front.

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CHAPTER I

INTRODUCTION

Turfgrass is a common feature in the landscapes of cities. According to the National Wildflower Research Center, urban turfgrass occupies an area equal to the size of the State of Michigan (National Wildflower Research Center 1990). 'Having a lawn' is deeply rooted in American culture. Over the years, it has become an indicator of good housekeeping and good citizenship (Jenkins 1994). A tremendous amount of water is used to fulfill this cultural expectation. In Dallas, Texas, during the summer months, it was estimated that 60 percent of the city's water was used for lawn irrigation (Lowen 1991). In recent years, however, attitudes toward turfgrass as a sole landscape cover have been changing.

In the arid Southwest, local governments are forcing residents and businesses to change their ideas about what constitutes a landscape. For example, in 1998, the City of Las Vegas, Nevada, amended its zoning code to establish limitations on turfgrass coverage associated with the landscaping of new developments (Las Vegas Zoning Code 1998). These changes are not made without opposition. Both freedom advocates and the multi-billion dollar turf industry (Economic Research Service 1997) oppose restrictions placed on turfgrass usage. As a practical matter, however, population growth and water demands are making these restrictions a necessity.

Much of the changing attitude can also be attributed to a significant increase in water cost in recent years. Water pricing has been an effective conservation tool in convincing both residential customers and turfgrass managers to alter their irrigation management or reduce the amount of landscape area irrigated. In 1996, the Las Vegas Valley Water District's tiered prices increased by 24 percent and by 54 percent for average daily usage rates of 400 and 1,400 gallons, respectively (Las Vegas Valley Water District 1999). The result has been a reduction of turfgrass utilization in residential areas. It seems, however, that turfgrass will remain a dominant cover at parks, golf courses and schools.

Large acreages of turfgrass in urban areas, however, remain for three purposes: (1) to buffer deleterious environmental conditions (e.g., control wind and water erosion, reduce runoff, provide climatic cooling, dissipate noise and glare); (2) for aesthetic use (e.g. to enhance property value and provide a pleasant environment); and (3) for recreational use (Georgia Institute of Technology 1990).

In Nevada, the Southern Nevada Water Authority (www.snwa.com) estimates that current water supplies can meet future water demands to the year 2025, but only by responsible conservation and full utilization of southern Nevada's existing water resources. It is, therefore, important that southern Nevada explore additional methods of both conserving and reusing those resources. Utilizing reclaimed, recycled and poor quality groundwater addresses both of these concerns.

Most of the effluent treated at the waste-water treatment facilities of Clark County and the cities of Las Vegas and Henderson is discharged into the Las Vegas Wash where it eventually flows into Lake Mead. Presently, a portion of the treated waste-water is reclaimed for use in irrigating parks, golf courses, highway landscapes, and mortuaries and for dust control activities (www.snwa.com). In the near future, the City of Las Vegas and Clark County plan to open recycling facilities on the west side of the Las Vegas valley that would each process 10 million gallons per day of primarily residential effluent (Grinell 1999). The major advantage of reclaimed and recycled waters is cost. The cost of reclaimed water is approximately 30 percent of the cost of potable water (Zikmund 1999). The cost of recycled water in the long term is also substantially less expensive (Zikmund 1999). As a result, turfgrass managers have become more open to using reclaimed effluent (Hayes, Mancino, Forden, et al., 1990; U.S. Golf Association 1994) and poor quality groundwater (Devitt 1989; Dean et al., 1996; Dean-Knox et al., 1998) as alternative sources of irrigation water.

Since recycled and reclaimed waters are more saline than potable waters, using them requires a more quantitative approach to irrigation management (Bresler et al., 1982; Oster 1994). Turfgrass managers need to know the chemical quality of the irrigation water so they can develop proper irrigation management strategies (U.S. Golf Association 1994). They also need to maintain accurate water and salt balances to prevent the combination of matric and osmotic stresses from exceeding turfgrass salinity threshold values (Dean et al., 1996).

Turfgrass managers must also understand the interaction between leaching fractions (LF = drainage volume/irrigation volume) and irrigation uniformity distributions in order to control the spatial distribution of water and salts and the response of plants to that distribution (Letey 1985; Leskys et al., 1999). Irrigators typically compensate for poorly designed irrigation systems by over-watering so that the low distribution areas obtain a threshold volume of irrigation. Over-watering is problematic not only because it increases water costs but also because it can promote environmental contamination in high distribution areas due to excessive leaching.

This field study was undertaken to determine the response of tall fescue turfgrass to saline irrigation water (2.5 dS m^{-1}) and varying LFs (0.05, 0.15, 0.25) and uniformity distributions (0.65, 0.75, 0.85). Tall fescue is a prevalent turfgrass in southern Nevada. The level of salinity used approximated the mean salinity (2.6 dS m^{-1}) existing in Las Vegas Wash water before it enters Lake Mead. Turfgrass response was assessed by measuring the spatial distribution in canopy temperatures, soil water contents, plant tissue water contents, matric potentials, soil salinity and chloride concentrations. Turfgrass response was also correlated with irrigation (I) and potential evapotranspiration (ET_o) data.

CHAPTER II

REVIEW OF RELATED LITERATURE

Plant Response to Salinity

Salt Tolerance

Irrigating with saline waters will eventually result in the excessive accumulation of salt in the root zone, unless adequate drainage is provided. Soil salinity is the most prevalent problem limiting crop production in irrigated agriculture (Shelhevet 1994). The most common result of salt accumulation is a general stunting of plant growth. The magnitude of this effect is dependent on the stage of plant growth, on the duration of salt exposure and on the variety of plant. Plants are more sensitive to salinized irrigations during the seedling stage than during the later stages of growth (Shelhevet 1994). At salt levels that inhibit shoot growth, root growth will often be unaffected. As a result, an increase in the root $shoot^{-1}$ ratio is observed when plants are subjected to salt stress (Cheeseman 1988).

Salt tolerance is usually defined as the yield decrease expected for a given level of soluble salts in the root medium as compared with yields under non-saline conditions (Maas and Hoffman 1977). In a study done to quantify salt threshold values, Maas and Hoffman (1977) found that when maintaining a high leaching fraction (0.5), tall fescue had a salt tolerance threshold of 3.9 dS m^{-1} in the saturation extract and a 5.3 percent yield-decrease per dS m^{-1}. However, Dean et al., 1996 found that when irrigating with water of 6.0 dS m^{-1}, tall fescue could still maintain adequate color and cover if irrigation practices were designed to minimize water deficit conditions.

Several studies have attempted to correlate soil-water EC with plant yield. The best estimate of effective salinity when salt is non-uniformly distributed with depth is the mean salinity within the root zone (Shelhevet 1994). Many crops seem less salt-tolerant when grown under hot dry conditions (Maas and Hoffman 1977). Seasonal differences in evapotranspiration rates generally increase soil-salinity levels. The results of a study using low quality irrigation water found that root zone EC levels were highest during the summer (10 and 14 dS m^{-1}) and lowest during the winter (2 to 4 dS m^{-1}) (Wu et al., 1996).

Osmotic Potential

For most plants, including turfgrass, there is a direct correlation between osmotic potential and response to salinity. Osmotic potential may be defined as the energy per volume required to move water from a pure solution with no solutes to a solution identical in properties and composition except for the addition of solutes. Irrigating with saline water will decrease the tissue osmotic potential. In order for a plant to acquire water through its root system from a soil containing high levels of soluble salts, the plant must lower its tissue osmotic potential. If the plant is unable to regulate the osmotic potential by sequestering or shunting these salts from the more sensitive organs, an eventual decline in plant performance occurs. The general effects that appear are retarded growth producing smaller plants with fewer and smaller leaves (Bernstein 1971). In a study conducted with tall fescue, it was found that significantly lower plant-water osmotic potentials were recorded under saline irrigation treatments (Dean-Knox 1998).

Osmotic potential in the soil solution can be measured indirectly by measuring the electrical conductivity of soil saturation extracts (EC_e) from the root zone, where the osmotic potential (bars) = -0.36 EC_{sw}. For many soils, the soluble salt concentration of the soil water (EC_{sw}), at field capacity, is about twice that at saturation (EC_e). Using EC_e as EC is recommended because the percentage of the saturation is easily determined in the laboratory and is related to the field-moisture range of soils varying widely in texture (Maas and Hoffman 1977).

While crop yield is the most important parameter in agriculture, turf color and cover present a greater concern to turfgrass managers. The influence of salinity on turf cover is complex since turf cover is a function of many variables such as tissue moisture content and canopy temperature. One study found that leaves produced under stress associated with salinity were 70% thicker than the leaves of control plants (Downton et al., 1985). Another study found that effluent irrigation (i.e. high salinity irrigation) caused significantly lower seed emergence when compared to turfgrass irrigated with potable water (Hayes, Mancino, and Pepper 1990). These studies suggest that there may be a range of salinity, specific to plant-type and irrigation management strategy that will maximize turf cover.

Turf color is generally a function of nitrogen and plant water status. From research done by Brown et al., 1997, it was found that there was a significant correlation, $r^2 = 0.91$ *** between turf moisture content and turf color. Dean et al., 1996, found that if the I/ET_o ratio was kept above 0.80, tall fescue maintained both adequate turf color and turf cover.

Salt Composition

The composition of salts in the irrigation water and soil can also factor into the response of plants. Any ion, in sufficient quantity, is capable of disrupting plant homeostasis. Studies have shown that increased concentrations of sodium, magnesium and chloride ions in plant tissue leads to decreased yields, particularly in arid and semi-arid regions (Oesterreichisches Forschungszentrum Seibersdorf 1994). Excessive sodium can replace potassium in plant tissue causing deleterious effects. Excessive sodium can also cause calcium replacement in cell walls and membranes (Greenway and Munns 1980). These conditions can be ameliorated by the introduction of divalent cations (e.g. calcium). If calcium is introduced in irrigation water as a means of amelioration, then care must also be taken in choosing its associated anion since it may have deleterious effects as well (Awada et al., 1995).

The concentration of sodium and its proportion to calcium and magnesium is important to both soil and plant quality. The sodium adsorption ratio (SAR) and the adjusted SAR are used to evaluate the suitability of waters for irrigation. High SAR waters can lead to problems associated with the deflocculation of clays and the sealing of pores. Excessive sodium accumulation in the soil can create dispersive soil conditions that will impede water transport through the soil profile (Jury et al., 1991).

Plant Response to Leaching Fraction

Leaching

The primary reason for irrigation water is for plant consumption, but there are other beneficial uses. Among these uses are crop-cooling, frost protection, soil preparation and deep leaching (Burt et al., 1997). The primary use of deep leaching is to leach salts from a root zone. The leaching fraction (LF) is defined as drainage volume divided by irrigation volume. Typically a 0.15 LF is recommended for most soils (Devitt 1989). If the LF is adequate for plant consumption, but not adequate enough to prevent salt build-up in the root zone, the plant will eventually begin to show signs of osmotic stress.

Excessive leaching, however, has its downside as well. High LFs can lower yield by leaching fertilizer or creating anaerobic conditions through saturation of the root zone (Heerman 1990). Contamination risks posed by excessive leaching can also effectively change management practices if the leaching threatens to contaminate groundwater (Guitjens 1997). In some areas of California, farmers are required to collect low-quality drainage and have it evaporate from collection ponds (Tanji and Grismer 1987). When excess leaching is necessary, it should take place when the soil salinity reaches hazardous levels (Shalhevet 1994).

Leaching Requirement

If the mass of the salt input exceeds the mass of the salt output, the salt balance is regarded as adverse, because this trend is in the direction of salt accumulation. One method of determining whether the field LF is adequate enough to prevent salt build-up is to calculate the leaching requirement (LR). LR refers to the fraction of irrigation water needed to obtain a prescribed level of salinity at the bottom of the root zone while providing adequate irrigation water for evapotranspiration. An estimation of LR can be made by summing the inputs and outputs of salt to the soil-water. The following equation represents this salt balance:

$$V_iC_i + V_gC_g + S_m + S_f - V_dC_d - S_p - S_c = \Delta S_{sw}$$

The positive variables represent the salt inputs and the negative variables represent the salt outputs. The variable V denotes volume; C denotes concentration and the subscripts i, g, and d represent the irrigation, ground and drainage waters respectively. The variable S_m is the amount of salts dissolving into the soil-water from weathering soil minerals and dissolved salt deposits. The variable S_f is the amount of salts added to the soil-water from the application of agricultural chemicals (e.g. fertilizers, amendments and animal manure). The variable S_p is the amount of salt out of the irrigation water that precipitates in the soil after application. The variable S_c is the amount of salt removed when the plant is mowed or harvested. The difference between the inputs and outputs is the change in soil-water salinity, ΔS_{sw}. Steady state conditions are reached when ΔS_{sw} equals zero. The salt balance equation can be simplified greatly if the following assumptions are valid: the groundwater table is sufficiently deep so that the root zone is unaffected by capillary action, the net effects of $S_m + S_f - S_p - S_c$ are zero, and steady state conditions have been attained. The salt balance equation can now be approximated by $V_iC_i = V_dC_d$ (Rhoades 1974). Since electrical conductivity is a reliable index of salt concentration (U.S. Salinity Laboratory Staff 1954), then $LR = V_d V_i^{-1} = C_i C_d^{-1} = EC_i EC_d^{-1}$.

Leaching and the root zone

The effects of osmotic and matric potentials on plant response are approximately additive (Wadleigh and Ayers 1945). Therefore, under saline conditions the soil-water content should be kept above a threshold quantity by irrigating more frequently than would be required under non-saline conditions (Rhoades 1974). A target LF does not have to be attained for every irrigation event, but can be averaged over the growing season (Rhoades 1974). This way, high and low transpirational plants can be rotated to maintain the target LF. For example, in the Imperial Valley, in California, vegetable production is included in a crop rotation with alfalfa because of slowly permeable soils and the high evapotranspiration rate of alfalfa (Rhoades 1974).

Yield generally declines as the osmotic potential increases, but for some plants, within limits, as long as part of the root system has access to soil-water of low salinity they are able to utilize some soil-water of higher salinity without adverse effects. It was found that even though tall fescue has a threshold tolerance of 3.9 dS m^{-1}, irrigations at a salinity level of 6.0 dS m^{-1} could be used if irrigation practices were designed to minimize water deficits (Dean-Knox et al., 1998). Forage grasses such as tall fescue develop bilayered root systems. These plants have one group of surface roots and a second group of roots that penetrate deep into the soil. Because of their surface roots, they are able to extract more water at the top of the root zone. Generally, for most plants, an approximation of water extracted from the root zone is 40%, 30%, 20% and 10% of the total transpiration requirements in each successively deeper quarter of the root zone (Wallach 1990). However, Devitt (1989) demonstrated that as profile salinization increased fractional water uptake in the near surface soil increased to as much as 59% as the plants became more dependent on the incoming irrigation water.

Plant Response to Uniformity Distribution

Non-uniform Irrigation

The result of non-uniform irrigation is that some areas of an irrigated field will receive either too little or too much water. Insufficient irrigation can cause matric stress, while excess irrigation can lower yield by either leaching too much fertilizer or creating anaerobic conditions through saturation of the root zone (Heerman et al., 1990). Excess irrigations are a result of water application practices that ensure that areas receiving the least amount of water are adequately irrigated. When irrigations exceed soil infiltration rates, the result is surface redistribution or runoff. Generally, un-infiltrated irrigation leads to poorer uniformity due to topographic puddling. Crops irrigated at lower uniformity distributions have been shown to require higher nitrogen applications in order to achieve the same yield attained while irrigating at higher uniformity distributions (Pang et al., 1997).

Younger plants suffer more from spatial fluctuations of irrigation water than do older plants, which have deeper roots. Water extraction by the roots can increase lateral unsaturated flow beyond that which occurs as a result of irrigation non-uniformity (Wallach 1990). Plant response is not only a function of the uniformity of sprinkler irrigation but can also be a function of the distribution of applied fertilizer, especially if the fertilizer is injected into the irrigation system (Ndiaye and Yost 1989).

Models

There are several statistical methods used to characterize uniformity distributions of irrigation water. Each method calculates a uniformity coefficient that statistically represents how uniform the sampled data (i.e. irrigation volume) is distributed. A uniformity coefficient of 1.00 implies that all data is uniform. In calculating the uniformity coefficient, each method makes different assumptions about the way the data is distributed. These distributions can be mathematically represented by distribution models such as linear, normal, gamma and beta distributions. In one study, 2,450 widely varying sprinkler irrigation patterns were used to determine which of the distribution models most accurately represented irrigation sampling results (Elliott et al., 1980). The study concluded that the linear model most accurately represented low uniformity sampling results while higher uniformities were better represented by the normal model.

For uniformity coefficients below 0.65, the linear model provided a better fit to the data (Elliott et al., 1980). A linear model assumes that over a given depth interval, the probability of observing one application depth is equal to the probability of observing any other application depth, i.e. a histogram of the application depths would be linear (Karmeli 1978). For uniformity coefficients of 0.65 and greater, a normal distribution provided a better fit to the data. One widely used method of describing normal distribution uniformity is the Christiansen uniformity coefficient (CUC) or the Hart and Reynolds (1965) modified CUC. The modified CUC is equal to $1 - (0.8s)\,x^{-1}$, where s is the sample standard deviation and x is the mean. This coefficient assumes that approximately 0.8 of the irrigated area receives an irrigation volume of at least the "average irrigation value" multiplied by the CUC.

Most uniformity distribution models only account for surface distribution. There may also be significant redistribution in the soil. The water available to a plant is influenced by the extent and distribution of the root system and the soil hydraulic conductivity. The effective uniformity distribution may be higher than what is measured at the surface (Heerman et al., 1990).

Variables Affecting Uniformity Distribution

Even where an irrigation system has been designed to optimize the application of water through the proper choice of sprinkler heads and spacing, other factors can affect uniformity distributions. These other factors include (1) operating pressure, (2) maintenance of the irrigation system, (3) wind speed, and (4) miscellaneous variables.

Operating Pressure

Sprinkler systems are designed to ensure proper overlap. An integral component of sprinkler system design is maintenance of the spray profile. The spray profile is pressure-dependent. When operating pressures are too low, there is insufficient irrigation close to the sprinkler head and when the pressure is too high there is excess irrigation close to the sprinkler head (Choate, 1984). The following equation can be used for sprinklers and emitters: $Q = cP^x$, where Q is the flow rate, c is a constant that depends on emitter or nozzle geometry, P is the pressure and x is a discharge exponent which is usually 0.5 for sprinklers (Burt et al., 1997). For large irrigation systems, likely locations contributing to overall poor uniformity are those most distant (Burt et al., 1997).

System Maintenance

In order to maintain uniformity distributions at a high level, turfgrass managers must continuously maintain the irrigation system. There is, however, a point of diminishing returns where any increased effort in maintaining a higher uniformity costs more than the sum benefit of water savings, increased yield or increased performance (Seginer 1987).

Some of the components which most often require maintenance include worn nozzles, mixed-size nozzles, nozzle plugging, sticking risers, non-vertical orientation of the sprinkler heads, improper placement of sprinkler heads and inaccurate pressure gauges (Burt et al., 1997).

Wind speed

If wind speed is not excessively high, direct evaporation losses from sprinkler irrigation are generally minimal, although evaporation losses from the plant surface can be high if the environmental demand is also high. A study conducted in South Dakota found less than 1.5% evaporation losses when winds were less than 6.9 m s^{-1} (15.4 mph) (Kohl et al., 1987). Another study found that evaporation losses under arid conditions (Arizona) can be neglected since the evaporation loss is approximately equal to the reduction in evapotranspiration during irrigation (Frost and Schwalen 1960). With regard to uniformity distribution, wind speed is important when it exceeds 1.8 – 2.0 m s^{-1} (4.0 – 4.5 mph) (Mateos 1998). A study performed in Kansas measured approximately 15% irrigation losses from wind drift and evaporation. (Steiner et al., 1983). Uniformity problems are made more complex when the wind is variable rather than persistent. When the wind is persistent, all sprinklers will behave similarly and irrigation spray will merely shift. When the wind is variable (a more common event), the uniformity distributions are more unpredictable (Seginer 1987).

Persistent wind distorts sprinkler irrigation by shifting its center of mass downwind. The wind narrows spray width normal to wind direction and elongates spray in the downwind direction (Seginer 1987).

In many cases, it was found that when sprinkler heads were positioned in a rectangular spacing grid, with the shorter side perpendicular to the wind direction, the result was better uniformity distribution (Seginer 1987). Non-uniformity caused by excessive wind can also be reduced by closing the distance between sprinkler heads and lowering the riser height (Heerman 1990).

Other sources of non-uniformity

Other sources that contribute to the non-uniformity of irrigation waters are soil-type, sprinkler applications exceeding infiltration rates and the existence of microtopographic effects (i.e. an unlevel field). These conditions result in surface redistribution or runoff and tend to reduce uniformity (Seginer 1987). Another variable is the lateral water potential gradients in the root zone. These gradients tend to increase uniformity (Hart 1972), but there is little experimental evidence showing horizontal redistribution in the field (Seginer 1987). It can be assumed that in well-managed fields the interaction between topographic effects causing runoff and lateral potential gradients is small (Seginer 1987).

There is also the possibility of errors associated with uniformity measurements. Irrigation uniformity distributions are most often measured by systematically spacing catch-cans in a rectangular grid pattern. When measuring the sprinkler uniformity distributions, the volume of irrigation not caught by the catch-cans can result in lower than actual irrigation estimates. In one study, approximately 20% of the irrigation was not accounted for when catch-can heights were 0.8 m and winds exceeded 3.4 m s^{-1} (7.6 mph)

(Livingstone et al., 1985).

CHAPTER III

METHODOLOGY

From 1 March 1994 to 1 September 1995, an experiment was conducted at the Center for Urban Water Conservation at the University of Las Vegas, Nevada, to investigate turfgrass response to salinized irrigation as influenced by various leaching fraction and irrigation uniformity distribution treatments. The turfgrass chosen was Monarch tall fescue (Festuca arundinacea). Monarch tall fescue (tall fescue) is a moderately salt tolerant grass (Maas and Hoffman 1977) able to survive the summers of the arid Southwest without significant loss of color. Tall fescue was planted as sod on 18 plots. Plot surface areas were 6.1 meters squared or 5.5 meters squared. The larger plots were used for low irrigation uniformity distribution; the smaller plots received high and medium uniformity distributions. The plots were spaced 6 meters apart from each other, and were positioned in an approximate 5 x 4 grid pattern (Fig. 1). The perimeter buffer zone, outside the 5 x 4 grid, extended 6 to 12 meters. The buffer areas between the irrigation plots, as well as the perimeter buffer areas, were seeded with Monarch tall fescue grass.

The Soil Conservation Service (SCS) classified the native soil in the research area as a Weiser Loam (extremely gravelly fine sandy loam) (Speck and McKay 1985). It is generally described as skeletal, carbonatic, and thermic Typic Calciorthids (Speck and

McKay 1985). It has clay content of 5 to 18%, a $CaCO_3$ content of 40 to 60%, and is moderately to strongly alkaline (Speck and McKay 1985).

Each irrigation plot had a 7.5 cm Lawn Pop-up sprinkler (TORO 300 series stream rotor) located at each corner. Each plot had its own pressure regulating solenoid valve. Irrigation uniformity distributions were maintained by keeping the sprinklers level, debris-free and by adjusting the regulator pressures (35 ± 5 psi). Adjustments were made on a monthly basis depending on uniformity testing results that were performed during the previous month under low wind conditions. Each plot also had a separate flowmeter to monitor irrigation volumes.

Before starting the experiment, the site was irrigated with low-salinity water (0.4 dS m^{-1}) for 4 months until uniform turfgrass conditions were established. Heavier than normal irrigations during this period also achieved leaching of native salts in the soil profile (0 - 45 cm). On 1 March 1 1994, irrigation with salinized water (2.5 dS m^{-1}) began. The salinized water was synthesized by adding calcium chloride and sodium chloride salts to deep aquifer groundwater on a 2:1 Ca:Na equivalent basis to obtain an electrical conductivity (EC) of 2.5 dS m^{-1}. The synthesized water was stored in a 60,000 gallon reservoir and was sampled and analyzed weekly ($x = 2.5$ dS m^{-1} and $s = 0.5$ dS m^{-1}). EC measurements were made using an electrical conductivity bridge (Beckman Industrial Conductivity Bridge, Model R-20).

Irrigation uniformity distributions were calculated using the Christiansen Uniformity Coefficient (CUC) adjusted by Hart and Reynolds (1965), so that $CUC = 1 - (0.8s)\,x^{-1}$, where s is the sample standard deviation and x is the mean. Every irrigation plot was assigned a uniformity distribution goal. Low uniformity distributions targeted a

CUC of 0.65, medium uniformity distributions targeted a CUC of 0.75 and high uniformity distributions targeted a CUC of 0.85. Uniformity distribution measurements were made by systematically spacing 25 catch-cans on an irrigation plot in a 5 x 5 grid pattern. These measurements were made during each irrigation event for a total of 450 such measurements during the experiment.

Each plot was also assigned a leaching fraction (LF = drainage volume divided by irrigation volume) goal of 0.05, 0.15 or 0.25. There were two replicate plots for each combination of CUC and LF factors making a total of nine different treatments for the 18 test plots.

A drainage lysimeter (61 cm diameter x 120 cm height) was centrally located in each plot (Fig. 2). At the bottom of the lysimeters were two ceramic porous cups surrounded by 10 centimeters of diatomaceous earth. The ceramic cups were connected to a collection bottle located in a belowground box adjacent to the plots. The collection bottles were connected to a vacuum pump capable of maintaining a vacuum of 13 cm Hg. Drainage was collected during every irrigation event. Each lysimeter contained the same native surface soil used throughout the research site. The soil in the lysimeter was screened (5.5 mm mesh) and packed at field bulk density levels (~ 1.6 g cm^{-3}).

Centrally positioned in each lysimeter was a stainless steel access tube (110 cm). A neutron probe (Troxler model 3300, Troxler Electronic Laboratories, Research Triangle Park, NC) was lowered into each access tube to indirectly estimate soil volumetric water contents (θ) on a weekly basis.

Future irrigations were determined by maintaining a hydrologic balance and inputting data collected from the previous week. Change in soil water in storage (ΔS) was estimated by integrating soil volumetric water contents measured at 20 cm, 40 cm, 60 cm and 80 cm over the entire soil profile. Drainage (D) was calculated by summing drainage collected in the collection bottles during irrigation events (Fig. 2). Irrigation (I) was calculated by summing the irrigation volumes collected by the catch-cans located at each lysimeter. Evapotranspiration was calculated using the hydrologic balance approach, $ET_a = I - D - \Delta S$ (note: when precipitation was detected it was included in the irrigation total of the hydrologic balance). ET_a and the assigned LF were substituted into the equation $I = [ET_a (1 - LF)^{-1}](CF)$. The correction factor, CF, was a plot-specific ratio of the "average lysimeter catch-can volume" divided by the "average plot catch-can volume". The value of CF ranged from 0.80 to 1.15. Finally, given plot-specific pressures, the irrigation volumes were converted to irrigation times.

Meteorological data was obtained from an automated weather station (Weather Watch 2000, Campbell Scientific, Inc., Logan, UT). The weather station was situated at the center of the research site. On an hourly basis, it measured and downloaded the following parameters: average solar radiation, average wind direction and velocity, average temperature, average relative humidity and rainfall. Hourly potential evapotranspirations (ET_o) were calculated by inputting these parameters into a modified Penman Combination equation (Campbell Scientific, Inc., Logan, UT).

Soil samples were taken before initiation of the experiment, at 12 months after the start of the experiment and at the end of the 18-month salinization period. Each irrigation plot was systematically sampled in a 6 x 6 grid pattern. Augers were used to obtain soil samples at depths of 0-15 cm and 15-45 cm. These samples were analyzed for gravimetric water content, EC_e and chloride concentrations. Chloride concentrations were measured with a chloride specific ion probe attached to a pH meter (Fisher, model 810, Santa Clara, CA). Additionally, at the end of the 18-month salinization period, three low uniformity plots (LFs = 0.05, 0.15 and 0.25) and three high uniformity plots (LFs = 0.05, 0.15 and 0.25) were also sampled at depths of 75 - 90 cm, 165 - 180 cm and 255 - 270 cm (or until caliche was encountered). These soil samples were analyzed for EC_e and chloride concentration.

Tensiometers to measure soil matric potentials were installed to a depth of 30 cm in three low LF plots having low, medium and high uniformities. On a weekly basis, a pressure transducer was inserted into the tensiometers to measure pressures (0 to 1000 mbars).

Plant response was assessed by measuring the following plant parameters: canopy temperatures, tissue moisture contents [(g fresh tissue – g dry yield) (g fresh tissue)$^{-1}$] and dry-weight yields. Canopy temperatures (using an infrared thermometer, Everest Interscience, Tustin, CA) and tissue moisture contents were measured biweekly and obtained systematically by sampling each irrigation plot on a 5 x 5 grid. The canopy temperatures were taken during the hours of 11:30 A.M. to 1:00 P.M. If more than one infrared thermometer was used, one plot was measured by both thermometers to obtain a correlation between the thermometers. Dry weight yields were obtained weekly after the grass in each irrigation plot was cut to height of 5 cm. Cuttings of grass growing on top of the lysimeters were also taken weekly and measured separately.

Data collected from soil and plant response grid sampling was kriged using geostatistical software (GS+ 2.3). The kriged contour maps were used as a tool in assessing spatial variability induced by the treatment effects of LF and CU. The advantages of kriging over most other contouring methods is that it minimizes error variance. Data was also analyzed using multiple linear regression, analysis of variance (ANOVA) techniques and Spearman's rank correlations. Regressions were performed in a backward stepwise fashion, with deletion of terms occurring when p values for the t-test exceeded 0.05 (Anderson-Bell 1986). The Spearman's rank correlation is a nonparametric statistic that was used to estimate correlations between chronological sampling events (McClave and Dietrich 1991).

CHAPTER IV

FINDINGS OF THE STUDY

Actual vs. Imposed LFs and Uniformity Distributions

When the nine different treatments were averaged and then sorted by the averaged measured LF, they ranked as expected. The three treatments with the lowest LFs were those that were assigned a 0.05 LF, the next three ranked LFs were those that were assigned a 0.15 LF, and the highest three LFs were those that were assigned a 0.25 LF. The actual LFs, however, did vary from imposed values. The average measured LF treatments obtained were 0.06 ± 0.03, 0.17 ± 0.03, and 0.25 ± 0.05. The average daily irrigation volume based on lysimeter water balances was 0.33 ± 0.06 cm day^{-1} for 0.05 LF treatments, it was 0.38 ± 0.07 cm day^{-1} for 0.15 LF treatments, and it was 0.46 ± 0.04 cm day^{-1} for 0.25 LF treatments. The r^2-value for the imposed LF vs. measured LF was 0.85 with a slope of 0.98, significant at the $p = 0.001$ level (Table 1).

Similarly, when the nine different treatments were averaged and then sorted by the averaged measured uniformity distribution, they ranked as expected. The three treatments with the lowest uniformity distributions were those that had been assigned a low uniformity distribution, the next three ranked uniformity distributions were those that had been assigned a medium uniformity distribution, and the highest three uniformity distributions were those that were assigned a high uniformity distribution. The actual uniformity distributions, however, varied from imposed values. Average measured uniformity distribution treatments were CUC = 0.67 ± 0.04, CUC = 0.74 ± 0.02, and CUC = 0.80 ± 0.03 respectively (Table 1). The average daily irrigation based on lysimeter water balances was 0.35 ± 0.09 cm day^{-1} for all low uniformity distribution treatments it was 0.39 ± 0.07 cm day^{-1}, for medium uniformity distribution treatments, and it was 0.43 ± 0.02 cm day^{-1} for high uniformity distribution treatments. This apparent bias can be explained by the large standard deviations and that ET rates were higher for the higher uniformity distribution because of better plant response. The r^2-value for the imposed uniformity distribution vs. actual uniformity distribution was 0.77 with a slope of 0.66, significant at the p = 0.001 level. The standard deviation of the measured CUCs ≥ 0.75 was 0.07. For CUCs less than 0.75 the standard deviation was 0.11. The number of samples required to estimate the mean CUC within 10% and with 95% confidence was calculated based on LF and CUC treatments (Jury 1985). It was found that fewer samples were needed to estimate the mean within 10% at the highest LF and CUCs (n = 3) than at lower combinations of LF and CUC (n = 16). For all treatments, there was more CUC measurements taken than the minimum sampling number estimates. The sample numbers were based on the relatively windy field conditions that existed during this study.

Wind Speed

The average wind speed during the summer month irrigation times (April 1 to September 30, 8 A.M. to 4 P.M.) was 3.9 ± 1.4 m s^{-1} (8.7 ± 3.2 mph). The wind speed peaked in the late afternoon. The average wind speed at 4 P.M. was 4.5 m s^{-1} (10.1 mph). The average wind speed during the winter month irrigation times (October 1 to

March 31, 8 A.M. to 12 P.M.) was 3.1 ± 1.1 m s^{-1} (7.0 ± 2.5 mph). The average wind speed for all irrigations was 3.7 ± 1.8 m s^{-1} (8.2 ± 4.1 mph).

Salinity Results

Before salinized irrigations began, soil sampling was conducted on a 6 x 6 sampling grid for each plot. Analytical results indicated that the EC_e values, for the 0 to 15 cm sampling depth, ranged from 0.34 to 5.24 dS m^{-1}. The average EC_e value for this depth was 1.89 ± 0.80 dS m^{-1}. The EC_e values for the 15 to 45 cm sampling depth ranged from 0.47 to 9.60 dS m^{-1}. The average EC_e value for this depth was 2.04 ± 1.38 dS m^{-1}. Tables 2, 3, 4 and 5 describe the average EC_e values of the different treatment plots before salinized irrigations began.

Analytical results from soil sampling conducted one year after salinized irrigations began indicated that the EC_e values, for the 0 to 15 cm sampling depth, ranged from 1.41 to 9.74 dS m^{-1}. The average EC_e value for this depth was 6.44 ± 0.90 dS m^{-1}. The EC_e values for the 15 to 45 cm sampling depth ranged from 1.13 to 14.04 dS m^{-1}. The average EC_e value for this depth was 7.04 ± 1.86 dS m^{-1}. Tables 6, 7 and 8 describe the average EC_e values of the different treatment plots.

Analytical results from soil sampling conducted at the end of the experiment indicated that the EC_e values, for the 0 to 15 cm sampling depth, ranged from 1.19 to 35.85 dS m^{-1}. The average EC_e value for this depth was 9.45 ± 6.38 dS m^{-1}. The EC_e values for the 15 to 45 cm sampling depth ranged from 1.39 to 31.45 dS m^{-1}. The average EC_e value at this depth was 10.39 ± 5.93 dS m^{-1}. Tables 9, 10 and 11 describe the average EC_e values of the different treatment plots. When a simplified salt balance was performed using the equation, $V_iC_i = V_dC_d$, the values projected below the root zone were: for LF = 0.05, $EC_e \approx 25$ dS m^{-1}; for LF = 0.15, $EC_e \approx 8.5$ dS m^{-1}; for LF = 0.25, $EC_e \approx 5$ dS m^{-1}. The observed depth-weighted (0 to 45 cm) EC_e values were: for LF = 0.05, $EC_e = 12.5$ dS m^{-1}; for LF = 0.15, $EC_e = 10.6$ dS m^{-1}; for LF = 0.25, $EC_e = 7.1$ dS m^{-1}.

A significant CUC x LF interaction on depth-weighted soil salinity was observed (Table 12, Fig. 3). The greatest range in soil salinity occurred within the low LF and low CUC treatment, where EC_e values for the 0 to 15 cm depth ranged from 3.04 to 35.05 dS m^{-1}. Average depth-weighted soil salinities increased over two-fold when the low-CUC and low-LF treatment was compared with the high-CUC and high-LF treatment (15.9 dS m^{-1} vs. 7.0 dS m^{-1}, Tables 9, 10, 11, Fig. 3). The steepest decline in depth-weighted soil salinity was observed under increasing LFs at the lowest CUC, with only a small change occurring at the highest LF as CUC increased. Depth-weighted soil salinity decreased from 17 to 11 dS m^{-1}, at a LF of 0.05, when the imposed CUC increased from 0.65 to 0.85. After salinization, the CV of depth-weighted EC_e (0 to 45 cm) decreased as LF increased except at low uniformities (Table 13).

The number of samples required to estimate the mean soil salinity at both depths within 10% was calculated (Table 14) based on LF and CUC treatments (Jury 1985). Fewer samples were needed to estimate the mean within 10% at the highest LF and CUCs than at lower combinations of LF and CUC. However, in all cases except the 0-15 cm samples at medium and high CUC at 0.25 LF, sufficient variability existed such that the number of samples needed to accurately assess the mean within 10% (42 to 216 samples), needed to be higher than the 36 samples generated from a 6 x 6 grid.

Yield Results

Evapotranspiration (cm) and yield (kg m^{-2}) were positively correlated ($r^2 = 0.51$, $p = 0.001$) when all LF and CUC treatments were combined. A significant interaction between the LF and CUC on both total yield and ET was observed (4 df, $p = 0.05$). Yield was also positively correlated with irrigation volume ($r^2 = 0.45^{**}$, n = 18; Table 15), especially at the low CUC ($r^2=0.96^{***}$, n = 6). Yield increased over two-fold as the irrigation volume increased with LF at the low CUC, indicating how increasing irrigation volume can increase yield by offsetting low CUC. It was interesting to note the interaction between CUC and seasonal temperatures. Table 16 shows that during the hottest months there was a 30% difference in yield between the low and high LF treatments. During the colder months, however, there is only a 12% difference in yield. This may be of some consequence to turfgrass managers interested in reducing the labor costs associated with mowing. These results suggest that it may be cost-effective to keep LFs as low as possible during warmer months. Less yield will also translate into less irrigation since the amount of evapotranspiration will decrease. This course of action must, however, be weighed against the consequences of low LFs. Yield is indicative of the over-all health of the plants, therefore, decreasing yield too much will decrease plant performance. Low LFs can also lead to increased salt loading requiring increased leaching during the colder months.

Tissue Moisture Content and ΔT Results

Plant tissue moisture contents at the last measurement date, (g water) (g fresh tissue)$^{-1}$ were significantly influenced by both the LF and CUC with a significant LF by CUC interaction occurring (Table 12, Fig. 4). Tissue moisture content was lowest under a combination of low LF and low CUC. Tissue-moisture contents measured under the conditions of this experiment fell in the range of 0.61 to 0.71 g H_2O per g fresh tissue. This narrow range in tissue moisture contents, resulted in only 1 to 2 measurements required to estimate the mean within 10%. The coefficients of variation were similar for both tissue moisture content and ΔT (Table 17). The percentage of significant ($p = 0.01$) Spearman rank correlations (Fig. 5 and 6) between successive sampling events was much higher for tissue moisture content (23%) than for canopy temperature measurements (10%). This trend was even more evident at the $p = 0.05$ significance level, where Spearman rank correlations for tissue moisture content (39%) were greater than for canopy temperature measurements (10%). This suggests ΔT is a more responsive parameter reflecting the immediate plant condition more accurately than tissue moisture content. Tissue moisture content must be regulated more tightly by the plant to maintain control over the internal plant water potential. The average tissue moisture content and ΔT Spearman rank correlations increased as CUC decreased for all LFs (Table 17). The only exception was for the tissue moisture content of the high LF and high CUC treatment. These results suggest that plant response within low CUC treatments tended to be more consistent. Canopy temperatures were highest under the combination of low LF and low CUC (Fig. 7). A significant LF by CUC interaction was observed for end of experiment canopy temperatures (Table 12). Canopy temperatures declined in a similar pattern under increasing CUCs at the low LF (34.2, 33.3, and 31.1 °C) and under increasing LFs at the low CUC (34.2, 33.8, and 32.2 °C). Thus, the shift in canopy temperatures with increasing LF was similar to the response noted for the depth-weighted soil salinity LFs by CUCs (Fig. 3) but differed from the response of soil salinity to increasing CUCs at the low LF. The number of canopy temperature measurements required to estimate the mean within 10% ranged from 1 to 5 and decreased as LF and CUC increased (Table 14).

When the averaged ΔT over the last year of the experiment was regressed with the measured CUCs of the 0.05 and 0.15 LFs, the r^2 was 0.33 * for n = 12. The 0.05 and 0.15 LF treatments were also regressed against irrigation, where the r^2 was 0.51 ** for n = 12. The 0.25 LF treatments did not show significant correlation with either parameter. These results seem to suggest that at least for ΔT, uniformity distributions play a greater role at the lower LFs (LF $\leq$ 0.15).

Kriging Results

Soil salinity (0 to 15 cm), gravimetric water content (0 to 15 cm), tissue moisture content, and ΔT (canopy temperature minus ambient temperature) measurements were kriged to generate isopleth maps for each plot and parameter (Fig. 8 and 9). Only one plot per low CUC treatment at the three LFs and one plot per low LF treatment at the three CUCs are shown (Fig. 8 and 9). The range in isopleths for each parameter was held constant (based on evaluating the data from all plots) to allow for easier visual comparison. Increased areas of high salinity, low θ_g, low tissue moisture content, and increased ΔT were observed as the set LF and CUC declined. However, areas of high soil salinity and low gravimetric water content did not always correlate with the areas of the lowest tissue moisture content or highest ΔT values (low CUC at low and medium LF, Fig. 8). At the low LF and CUC, a significant portion of the plot had soil salinity values (0-15 cm) greater than 16 dS m^{-1} (75%) and gravimetric water contents less than 0.20 g H_2O per g oven-dried soil (56%). As the CUC increased at the same LF, soil salinity decreased and gravimetric water contents increased (Fig. 9), leading to subsequently higher tissue moisture contents and lower ΔT values. A similar trend was observed at low CUC as the LF increased. However, higher tissue moisture contents and lower ΔT values on an area basis were observed at the low LF and high CUC than at the low CUC and high LF. In fact, the most favorable plant water status on an area basis occurred under high uniformity at all LFs (Fig. 8 to 9).

Gravimetric Water Content Results

Gravimetric water contents (θ_g) [(g H_2O) (g oven-dried soil)$^{-1}$] were not significantly correlated with LF or CUC, nor was there a significant LF x CUC effect on θ_g. The depth-weighted (0 to 45 cm) CVs, associated with the gravimetric water content before salinized irrigations began, ranged from 0.10 to 0.25 (Table 18). During the last 6 months of the experiment the CVs ranged from 0.10 to 0.21 showing no trend with treatment type (Table 19). The average θ_g before salinized irrigations began was 0.22 ± 0.07 for the 0 to 15 cm sampling depth and 0.20 ± 0.05 for the 15 to 45 cm sampling depth. One year into the experiment, the average θ_g was 0.21 ± 0.03 for the 0 to 15 cm sampling depth and 0.18 ± 0.04 for the 15 to 45 cm sampling depth. At the end of the experiment, the average θ_g was 0.21 ± 0.03 for the 0 to 15 cm sampling depth and 0.19 ± 0.05 for the 15 to 45 cm sampling depth. Significantly fewer soil samples were needed to assess gravimetric water contents within 10% of the mean (Table 12) than were required for soil salinities, with a requirement as low as 3 for the sampling number.

Figure 10 shows that there were no significant correlations between CUC x LF and the depth-weighted soil gravimetric water contents. Surface soil gravimetric water contents are not generally a static parameter, but instead reflect the interaction of the most recent irrigation distribution and plant water uptake patterns. Variation in soil moisture (0-15 cm gravimetric water content) was not significantly correlated with the set LF and CUC treatments. Figure 11 shows the relative irrigation volume (irrigation volume measured in each cup in the 5 x 5 grid locations divided by the maximum irrigation volume measured) in one low-CUC x low-LF plot based on the average of 22 uniformity tests taken over the experiment. The figure also includes the soil gravimetric water contents (0 to 15 cm) measured at the end of 12 and 18 months of treatment. Although the soil gravimetric water content distribution suggested a zone of lower water content (locations 13-22, also Fig. 8) at the end of 18 months, this same pattern did not exist at the end of 12 months. In fact, grid locations with the lowest relative water contents at one sampling date were often associated with the highest values at the other sampling date. Thus, although the irrigation distribution was consistently poor (average CUC of 0.63), the long-term irrigation signature suggested that the same pattern was not repeated over time (average values between 0.4 and 0.7 of the maximum irrigation value at all locations). This phenomena may have been aided by changes in wind direction which regularly switch from a N - S direction in winter to a S - N direction in summer. However, unlike surface soil moisture, lysimeter soil water in storage (central location in plot, measured during the peak summer) was influenced by the LF and CUC, as these two parameters accounted for 75% of the variability in the measured storage values ($n = 18$, $p = 0.001$).

Plant Response and I/ET_o

Changes in the irrigation distribution treatments directly influenced the amount of variation associated with measured soil and plant parameters (Fig. 12). Although the coefficient of variation for each variable increased as CUC decreased, only the depth-weighted EC_e showed coefficients of variation greater than 20%. The relationship shown in Figure 12 indicates that the variation in soil moisture was more closely aligned to the measured plant variables than the soil salinity. This would be supportive of the findings of Dean et al. (1996), that tall fescue response to saline irrigation water (6.0 dS m^{-1}) is more closely linked to a threshold I/ET_o value than a threshold soil salinity.

Combined ΔT and Tissue Moisture Content

representing Plant Response

As measures of plant response, canopy temperature and tissue moisture content were each averaged over the last year of the experiment. They were then weighted equally and their summation normalized. These parameters were chosen because they best represent the stress conditions of the turfgrass, and because they are known to directly influence the turf cover and color. Yield was not included because it is not a parameter that turfgrass managers vie for. Both the canopy temperature and tissue moisture content were averaged over an extensive length of time for two reasons. The primary reason is that steady state conditions for most of the treatments had not been attained; therefore, end of experiment data would still not have represented steady state conditions. The second reason is to minimize the bias introduced by the variability associated with the parameters. An example of this variability was observed for successive canopy temperature measurements of the averaged LF = 0.15 and medium CUC treatment. This treatment ranked at the 98 percentile when compared to the other treatments on 7/25/95. Then the treatment ranked at the 73 percentile when compared to the other treatments on 8/15/95. On 8/29/95, the treatment ranked at the 53 percentile when compared to the other treatments. We believe the cause of this variability can be related to the complex interaction between environmental demand, root uptake, and change in soil water content and drainage. Figure 13 shows the CUC x LF interaction with plant performance.

This normalized plant response (plant performance) was plotted against the normalized sum of I/ET_o and the depth-weighted soil salinity (0 to 45 cm; Fig. 14). Turfgrass managers can control I/ET_o directly and the salinity indirectly by manipulating LF and CUC (based on results of this experiment) or by mixing various proportions of saline and non-saline waters. The I/ET_o and salinity variables were weighted equally. Figure 14 shows that the normalized sum of I/ET_o and salinity had the same approximate slope as the plant performance data set but oscillated about this slope. Regression of this normalized I/ET_o and soil salinity sum, with the normalized plant performance, resulted in an r^2-value of 0.47 **. Regression of depth-weighted soil salinity (0 to 45 cm) alone, versus the normalized plant performance resulted in an r^2-value of 0.42 **. Regression of I/ET_o alone, versus the normalized plant performance resulted in an r^2-value of 0.46 ** with an intercept of 0.35 and a slope of 0.57. If a threshold value of 0.80 is used for the I/ET_o ratio, then the resulting plant performance would be predicted to be 0.81 and the corresponding depth-weighted soil salinity 0 to 45 cm would be 8.8 dS m^{-1}. Among the other parameters that were regressed against the plant performance were the actual LF (r^2 = 0.45 **) and measured CUC (r^2 = 0.12).

<u>Rating Actual LF x Measured CUC x Plant Performance</u>

From Table 15 it can be seen that LF and irrigation are significantly correlated. The oscillating pattern, observed in Figure 14, for plant performances above 65%, demonstrates the unexpected behavior of low leaching plots that have similar CUCs but exhibit better plant performance. To investigate this behavior, each plot was compared with every other plot with regard to their actual LFs, measured CUCs and plant performances. There were 12 occurrences of plots having higher LFs and higher CUCs but poorer plant performance. Each of these occurrences was then further investigated with regard to salt loading as described by the depth-weighted soil salinity (0 to 45 cm). In all 12 occurrences it was found that even though the plots exhibited better plant performance they also had greater rates of salt loading in the soil profile. Because we had not reached steady state conditions, the better plant performance was perhaps not indicative of the possible future consequences related to the increased salt loading.

The alternative scenario occurs when higher leaching plots have lower CUCs and poorer plant performance than lower LF plots that have higher CUCs and better plant performance. This is expected behavior and it occurred 28 times. Over 50% (15 out of 28) of the occurrences involved the lower third leaching fraction treatments (i.e. imposed LF = 0.05). For example, plot S4 had an actual LF = 0.13 and a measured CUC = 0.79. Yet, its plant performance (as measured by previously mentioned criteria) was better than that of plot N1 that had an actual LF = 0.34 and a measured CUC = 0.75.

These occurrences were also investigated with regard to salt loading as described by the depth-weighted soil salinity (0 to 45 cm). Unlike the unexpected previous scenario, it was found that in 10 of the occurrences, there was less salt loading in the plot maintaining the higher CUC and exhibiting the better plant performance while maintaining a lower LF. For example, plot S8 had an actual LF = 0.07, a measured CUC = 0.75, and a depth-weighted soil salinity (0 to 45 cm) of 12.44 dS m^{-1}. Yet, its plant performance was better than that of plot S10 that had an actual LF = 0.14, a measured CUC = 0.71, and a depth-weighted soil salinity (0 to 45 cm) of 11.39 dS m^{-1}.

Plant Performance vs. I/ET_o, Depth-weighted soil salinity (0 to 45 cm), Water Savings

Plant performance was plotted against I/ET_o, depth-weighted soil salinity (0 to 45 cm) and water savings (Table 20, Fig. 15). All the data included in Fig. 15 was linearized in Figure 16. The plant performance was linearized in two parts (from the LF = 0.05 low CUC treatment to LF = 0.15 low CUC treatment, and from the LF = 0.15 low CUC treatment to LF = 0.15 high CUC treatment). For the second phase of the two-phase linear function, the r^2 was 0.96 *** and the slope was 0.055. The I/ET_o data was variable, but still significant with an r^2 = 0.72 **, slope = 0.040 [(cm water) (cm water)$^{-1}$]. The depth-weighted soil salinity (0 to 45 cm) had an r^2-value of 0.53 * and a slope of -0.80 (dS m^{-1}). Water savings data inversely mirrored I/ET_o data such that the r^2 was 0.72 ** and the slope was -7.9 (cm m^2 yr^{-1}).

From research done by Brown et al., 1997, it was found that there was a significant correlation, r^2 = 0.91 *** between turf moisture content and turf color (Fig. 17). Turf color was estimated for all plots based on the Brown moisture content correlation. When the plant performance data was plotted against estimated turf color and a threshold color rating of 8.0 was used, it was found that the threshold plant performance was 0.33. The 0.33 plant performance threshold corresponded with I/ET_o = 0.6. This compared with an I/ET_o threshold value of 0.8 for tall fescue (Dean et al., 1996) when the irrigation salinity level was 6.0 dS m^{-1}. At this threshold, all the treatments except for the LF = 0.05 low uniformity treatment were acceptable. When the criteria of 0.15 LF is used (Devitt, 1989) to determine acceptable treatment types, then by averaging the depth-weighted salinities of all of the LF = 0.15 treatments, an average value of 10.7 (dS m^{-1}) was found. Using this threshold, for the experimental conditions of this study, all but the following treatment types would be acceptable: LF = 0.05 low CUC, LF = 0.15 low CUC, LF = 0.15 medium CUC.

Soil chloride/EC Ratios vs. Soil Depth

At the near surface depths (0 to 45 cm), soil salinity and soil chloride distributions were very similar (Fig. 3 and 18). Anions are generally more mobile through a soil profile than cations. This increased mobility is demonstrated in Figure 19. The soil chloride/EC ratio decreases as depth increases. This leads to increased separation at the lower depths and decreased soil chloride/EC ratios. This trend begins to reverse itself at the lowest depths as demonstrated by the increased slope at 270 cm. Because of its mobility, soil chloride concentrations were used to determine the depth of the wetting front, and both soil chloride and EC_e concentrations were used to investigate the effect of uniformity distribution on leaching patterns through the soil profile.

Fingering activity based on EC_e data

Figure 20 shows depth profiles of EC_e concentrations. In order to investigate the possibility of localized deep leaching (fingering), EC_e values at sampling intervals were correlated with EC_e values of the sampling interval above. This was done for the plots that were sampled at deep depths (i.e. plots N4, S8, S4, S7, N9 and S2). First, the 0 to 15 cm soil depth was compared with the 15 to 45 cm soil depth. It was found that for the low leaching fraction plots (N4, S8, S4), the Spearman rank correlation between the soil depths was significantly higher for the medium and high uniformity treatments than for the low uniformity treatment, r = 0.84 **, r = 0.83 ** and r = 0.07; Table 21. This trend, though no longer significant, continued between the 15 to 45 cm and 75 to 90 cm depths (r = 0.35, r = 0.27 and r = 0.00; Table 21). These trends suggest that the higher CUC plots had greater uniformity in the vertical direction. Tensiometer data indicated greater matric stresses were present in the low LF and low CUC treatment. These potentials would have, to a greater degree, diverted soil-water in horizontal directions. Since lateral redistribution of soil-water tends to reduce vertical rank correlation, treatments resulting in higher matric stresses would be expected to demonstrate lower rank correlations. The trend reversed when comparisons were done between the 75 to 90 cm and 165 to 180 cm soil depths (r = 0.08, r = 0.29 and r = 0.63 **; Table 21). The rank correlations at these deep depths may have provided support for fingering activity for the low CUC plot (N4) if the salt front reached those depths. Figure 19 indicates that very little, if any, water reached that depth for plot N4. It must be noted, however, that fingering activity could have easily existed between sampling locations since on a surface area basis, only 0.2% of each plot was sampled.

The same investigation was done for the higher leaching fraction treatments (S7, N9 and S2). It was found that for the low CUC treatment (S7), the Spearman rank correlation between the 0 to 15 cm and 15 to 45 cm soil depths was significantly higher than for the medium and high uniformity treatments (r = 0.96 **, r = 0.25 and r = 0.68 **; Table 21). Additionally, the CV was also significantly higher for the low CUC treatment at that depth (i.e. compare 0.66 ** with 0.23 and 0.20). These findings suggest comparatively non-uniform wetting front for the low uniformity treatment and this supports the assumption that fingering is greatest for high LF treatments with low CUCs.

This trend continued for the deeper depths. Both the Spearman rank correlations and CVs were dependent on CUC. For the 15 to 45 cm and 75 to 90 cm depths; r = 0.75 ** CV = 0.56, r = 0.49 * CV = 0.28 and r = 0.22 CV = 0.26. For the 75 to 90 cm and 165 to 180 cm soil depths; r = 0.74 ** CV = 0.55, r = 0.44 * CV = 0.18 and r = 0.34 CV = 0.21, for the low, medium and high uniformity distributions, respectively (Table 21).

Fingering activities based on soil chloride data

Poor uniformity can lead to areas of excessive collection of irrigation water that in turn can lead to localized deep leaching (fingering). Such a worse case scenario should exist under high LF and low CUC. It is possible that this condition may also exist for low CUC at lower LFs. One interesting result mentioned earlier was the significant EC_e Spearman rank correlation for the low uniformity plot (N4, r = 0.63 **), at the 165 to 180 cm sampling depth. If there was leaching to this depth, this high correlation supports the existence of fingering since fingering tends to follow vertical paths. The low uniformity plot (N4) also had a relatively higher (though not significant) soil chloride Spearman rank correlation between the 75 to 90 cm and the 165 to 180 cm sampling depths than the higher uniformities (r = -0.31, r = -0.10 and r = 0.07; Table 22, Fig. 21). The higher LF soil chloride rank correlations were similar to the salinity rank correlations except at the deepest depth (Fig. 22).

It is, however, necessary to determine whether the low leaching plots had any drainage reaching the 165 to 180 cm sampling depth. This was done by comparing soil chloride concentrations at the 165 to 180 cm depth with a background soil chloride concentration. The background soil chloride concentration was first determined. To ensure no influence from irrigation activities, only samples obtained at depths of 270 cm or greater from low leaching plots were used to estimate the background soil chloride concentration. The average background soil chloride concentration was found to be 13.6 ± 16.6 meq l^{-1} (n = 50). Figure 23 shows the soil chloride profile for the deep-sampled treatments. The figure suggests that for the low leaching plots, the bulk of the irrigation water had not leached much farther than the 15 to 45 cm sampling depth. The average soil chloride concentrations for the low CUC and low LF plot at the 165 to 180 cm depth, however, was almost 2 standard deviations higher than the background concentration (43.4 ± 35.3 meq l^{-1}). It is possible that background chloride concentrations decreased with depth which may explain the higher concentrations found at this depth. The wider range of soil chloride concentrations for the low CUC and low LF plot, however, provided additional evidence that fingering had reached the 165 to 180 cm depth for plot N4 (i.e. compare the range 6.6 meq l^{-1} to 151.4 meq l^{-1} with the ranges 1.8 meq l^{-1} to 31.2 meq l^{-1} and 2.2 meq l^{-1} to 57.8 meq l^{-1}). Both of the low LF and higher CUC plots did not have significantly higher average soil chloride concentrations than the background concentration (14.4 ± 7.4 meq l^{-1} and 22.8 ± 18.5 meq l^{-1}). This may provide strong evidence for relatively greater fingering activity in plot N4 since it had a lower actual LF than the higher CUC plots (i.e. compare LF = 0.05 with LF = 0.07 and LF = 0.13).

It is not totally clear from Figures 3 and 19 whether wetting fronts reached the 1.8 meter depths. To determine if it was possible for fingering effects to reach that depth, a maximum infiltration condition was investigated. The saturated hydraulic conductivity (K_{sat}) of the soils in the lysimeters was measured using the constant-head (Black 1965) laboratory method. It was found that the K_{sat} was approximately 1.7 x 10^{-2} m day^{-1}.

Assuming similar saturated conditions in the plot outside the lysimeter and the absence of macropore bypass, then the expected maximum depth of wetting would be 9.3 meters over the duration of the experiment. It then seems likely that if soil gravimetric water contents were large enough, $K_{unsat}(\theta_g)$ would approach K_{sat} and substantial fingering activity would have reached the 1.8 meter sampling depth.

Among the deeper depth sampled plots (S7, N9 and S2), the three high leaching treatments were investigated for evidence of fingering. It was found that even though the lowest CUC treatment (S7) had the lowest actual LF (i.e. compare 0.23 with 0.30 and 0.32), it had the largest range of soil chloride concentrations (i.e. compare 3.4 to 140.1 meq l^{-1} with a range of 19.3 to 95.1 meq l^{-1} or a range of 14.9 to 60.8 meq l^{-1}). The range of soil chloride concentrations is significant since the soil chloride concentration front is dictated by LF and plant uptake. Higher concentrations can be a result of a concentrating factor caused by water uptake by the roots. Lower concentrations can indicate excess local irrigation above and, as a result, fingering below. Additionally, it is interesting to note that both the soil chloride Spearman rank correlations and CVs increased as CUC decreased for all deep-sampled treatments (N4, S8, S4, S7, N9 and S2) up to 90 cm depths (Fig. 11 and 12). This seems to support a situation of more uniform wetting among the higher uniformity treatments and more prevalent fingering in the lower uniformity treatment. The same trend was demonstrated for salinity (Fig. 24 and 25) except, interestingly, for the low CUC and low LF treatment at the 15 to 45 cm and 75 to 90 cm depths. A possible explanation for the change of trend might be that because the low CUC and low LF treatment had less irrigation than the other plots, the irrigation that it did receive was laterally distributed to a greater degree as a response to matric and osmotic gradients.

Figures 26, 27 and 28 show the predicted LFs of the treatments based on soil chloride analysis of the irrigation and drainage waters. Steady state conditions are met when the predicted LF equals the actual LF. When the actual LF was regressed with the ratio of the actual over the predicted LF, the r^2 was 0.74 ***, and the slope was 2.9. Higher LFs were closer to steady state conditions. It was found that the average actual LF of the treatments within 10% of steady state conditions was 0.30 (n = 3). For these treatments, the average EC_e was 8.5 dS m^{-1}. Measured CUC did not have a significant correlation with the actual over predicted LF ratio, and it was not expected, since steady state conditions were monitored only within the confines of the lysimeter.

Difficulties with experiment

Irrigation water from a deep aquifer (EC = 0.4 dS m^{-1}) was used to flush dissolved and mineral salts from the root zone. The amount of residual low EC water in the root zones may have biased upwardly the plant performance of the low leaching treatments especially during the early phase of the experiment. This effect was assessed by investigating water balances in the lysimeter. The total volume of a lysimeter was approximately 350 liters. The average background depth-weighted (0 to 45 cm) soil gravimetric water content was 0.21. If the residual gravimetric water content was assumed to be approximately 0.05, then the volume of deep aquifer irrigation water residing in the lysimeters at the time that salinized irrigation began would be approximately 56 liters. It is expected that the plants would have extracted the low-EC water residing in the upper root zone. The upper root zone ranges from the surface to approximately 45 cm deep, so that of the 56 liters, approximately 21 liters would have been removed. That leaves approximately 35 liters of low EC soil-water in the lysimeter when the experiment began. Of the low leaching treatments two of them had cumulative drainage volumes of less than 35 liters. The other four had 11%, 51%, 96% and 122% greater drainage volumes. Because of this dilution, the drainage results from the lower leaching treatments may have been biased so that salt-loading estimations may have been lower than expected.

Among the uncontrolled variables which may have affected the experimental results were precipitation and wind speed. Precipitation was included in the hydrologic balance, however, the diluting effect it had on irrigation salinity was not accounted for. It was found that precipitation was 3% of the total average irrigation received by the 0.05 LF treatments. The diluting effect of this small proportion is considered insignificant when compared to the EC standard deviation of the irrigation water (i.e. where the average EC level was 2.5 dS m^{-1} and s = 0.5 dS m^{-1}). Wind speed had a very large effect on CUC values. Both the magnitude and directional changes caused rather large standard deviations and averaged CUC values that were less than desired for the higher uniformity treatments.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The LF and CUC are two irrigation parameters that managers have the ability to alter. Optimizing these parameters when using poor quality waters can lead to more favorable growing conditions. Although an economic assessment was not part of the research objective, based on current urban water costs in the Southwest (as much as $60 per ha cm in Las Vegas, NV), minimizing the LF could lead to substantial water and dollars savings. Based on the approach of Rhoades (1974), the leaching requirement for tall fescue irrigated with water possessing an electrical conductivity of 2.5 dS m^{-1} would be 15%. Previous work by Dean et al., 1996, indicated that the ratio of I/ET_o of tall fescue could be as low as 0.80 and still not be associated with significant loss in color or cover when irrigated with saline water of 6.0 dS m^{-1}. At this I/ET_o threshold, the average soil-water salinity was 10.2 dS m^{-1}. If this 10.2 dS m^{-1} EC_e was then inserted back into the Rhoades (1974) equation, a leaching requirement of only 5% would be predicted. This prediction was in general agreement with the low LFs predicted in this study.

Using the approach of Maas and Hoffman (1977) and the relative yield of 0.49 at an I/ET_o of 0.80 (Dean et al., 1996) an EC_e of 13.5 dS m^{-1} would be generated, which still provided excellent color and cover ratings (Dean et al., 1996). In this study, only the low CUC and low LF treatments had average depth-weighted soil salinities greater than this concentration. Both the medium (actual LF of 8%) and high CUC (actual LF of 12%) treatments had maintained acceptable turf color and turf cover, suggesting an LF of 8% could be applied if uniformities were kept high enough.

In this study, this same assessment is arrived at using a different approach. Brown et al., 1997 found that there was a significant correlation, $r^2 = 0.91$ *** between turf moisture content and turf color (Fig. 17). Turf color was estimated for all plots based on the Brown moisture content correlation. When the plant performance data was plotted against estimated turf color and a threshold color rating of 8.0 was used, it was found that the threshold plant performance was 0.33. The 0.33 plant performance threshold corresponded with $I/ET_o = 0.6$. Therefore, this study indicated that I/ET_o could be as low as 0.6 and not be associated with significant loss in color when irrigated with saline water of 2.5 dS m^{-1}. If this I/ET_o value substituted into the linearly regressed equation between depth-weighted salinity and I/ET_o ($r^2 = 0.76$ ***), then an EC_e of 12.7 dS m^{-1} would be generated. At this salinity the same treatments would be considered acceptable, and therefore, suggesting a LF of 8% could be applied if uniformities were kept high enough.

In our experiment a comparable plant response was observed between the imposed 0.25 LF treatment at the low CUC and the imposed 0.05 LF treatment at the high CUC (Table 20). However, a 14 % savings in irrigation volume was obtained when the CUC was optimized at the imposed 0.05 LF over the imposed 0.25 LF with a low CUC. Increasing the CUC forced the irrigation volume up, by 39% at imposed 0.05 LF and by 27% at imposed 0.15 LF. These higher irrigation requirements at the higher CUCs were typically associated with more favorable growth. This higher growth fueled higher ET rates and subsequently higher irrigation requirements. However, at the imposed 0.25 LF, irrigation volumes decreased by 5% as the CUC increased from imposed 0.65 to imposed 0.85. Increasing the LF at the same CUC forced the irrigation volumes up by 74% at the imposed 0.65 CUC, 29% at the imposed 0.75 CUC and by only 10% at the imposed 0.85 CUC.

Although LFs on a field-scale basis indicate a drainage component to the water balance, the LF alone provides a false sense of security with regards to preventing deficit irrigated conditions from existing on a subplot scale. Jensen (1975) indicated that if water applied to 10% of the field regularly receiving the least amount of water had a LF of 0.05, the average LF for the entire field would have to be five-fold higher as the CUC dropped from 1.00 to 0.90. Thus, at lower CUCs if the LF is not exceedingly high, parts of the field will be deficit-irrigated. However, plants growing in these deficit-irrigated areas are not always the most stressed, as the redistribution of soil moisture with depth is greatly influenced by lateral water potential gradients established under uneven water distribution (Hart 1972) and because rooting patterns respond to this shift in water distribution. Therefore, the effective uniformity response of a crop may be higher than the uniformity of the applied water (Heerman et al., 1990; Seginer 1987). With time, if poor quality water is used for irrigation, deficit-irrigated areas become zones of salt accumulation eventually exceeding the plant's soil salinity threshold value.

In our study, average depth-weighted soil salinity increased as both the LF and the CUC decreased. However, plant response as indicated by canopy temperature and tissue moisture content did not have the same distribution as soil salinity on a subplot scale (Fig. 4 and 5). Dean et al., 1996, suggested that color and cover of tall fescue was linked more to I/ET_o thresholds than soil salinity. Although the soil salinity threshold value of

3.9 dS m^{-1} was exceeded at most grid locations in all treatments, based on the plant response in this experiment, an I/ET_0 threshold of 0.6 was only exceeded under the worst-case scenario of low LF and low CUC (Fig. 15). Soil salinity values in the 0 to 15 cm zone of the low LF, low CUC treatment were as high as 35 dS m^{-1} in some locations. Such variation has a large impact on the sample number requirement needed to assess the mean soil salinity in the field to within 10%. Insufficient information associated with inadequate sampling can lead to inaccurate long-term predictions as to the suitability of using poor quality waters for irrigation purposes. It was disappointing to discover that a grid sampling of at least 10 x 10 per 37 m^2 surface area would be needed to properly assess the variation in soil salinity associated with the low CUC irrigation plots. Such sample number requirements do not bode well for the development of accurate soil-plant-water models in the field for conditions described in this experiment.

Sensitivity of yield to CUC was clearest at the lowest LF. This would be in agreement with the results reported by Warrick and Yates (1987) where yield was more sensitive to the distribution as the average water added approached the threshold value. Seginer (1987) developed equations to predict the loss in cotton yield with loss in uniformity at varying levels of seasonally available water. Yield losses of as much as 0.5% were predicted for each 1.0% loss in uniformity. In our study, yield losses of 2.63% per 1.0% loss in uniformity occurred at the low LF, 2.13% at the medium LF, and a 0% loss at the high LF. However, plant water status on an average plot basis changed at or below 1% for each 1% loss in uniformity (ET, 1.1%, 0.3% and 0%; tissue moisture content, 0.6%, 0.3% and 0%; canopy temperature, 0.6%, 0.4% and 0.3%, at low, medium and high LF, respectively). We believe that the difference in our results from Seginer's results were linked to a species-dependent response and the added variable of salinity. Seginer (1987) did note that low uniformites could have a profound effect not only on water balances but also on salt balances.

Fifty-five percent of the variability in the average plot depth-weighted EC_e values ($n = 18$, $p = 0.001$) was accounted for by the imposed LF and imposed CUC. Expanding the parameter list by including the actual LF, lysimeter ET, and average plot canopy temperature (end of experiment) accounted for 91% of the variability in the average plot depth-weighted EC_e values ($n = 18$, $p = 0.001$). However, the depth-weighted plot EC_e was eliminated in a backward stepwise regression when estimating plot yields. Fortunately, turfgrass yield is of little concern to most turfgrass managers. Canopy temperature, which is a good indicator of turfgrass stress (Dean et al., 1996), is an easier parameter to assess and is more closely correlated with turfgrass quality. In addition, a very low sample number is required to estimate the mean canopy temperature to within 10 % (Table 2). In our study, 76% of the variability in the final average canopy temperature measurements could be accounted for if actual LF, ET, and depth-weighted EC_e were included in the regression analysis.

Possible dollar savings associated with reducing the LF would probably only be acceptable to turfgrass managers if no significant loss in turfgrass quality occurred. To reflect true revenues, these dollar savings would need to take into account the impact irrigation uniformity has on applied water requirements, the cost of system upgrades, and plant response. Letey et al., 1984, showed that economic analysis which ignores infiltration uniformities underestimates optimal levels of applied water. At typical agricultural water prices (Letey-California, $7 ha cm, 1984, Coachella Valley Water

District, \$1.11 ha cm, 1998) the economic optimum applied water for corn increases with decreasing uniformity when water prices are low but the opposite occurs when water prices are high. Dinar et al., 1985, indicated that this economic optimum applied water is also more sensitive to water price when salinity of the irrigation water increases.

Evidence of localized deep leaching (fingering) was also investigated. Results of rank correlations between overlying sampling depths seem to indicate that lower CUC treatments provide more evidence of fingering activity than higher CUC treatments (Fig. 24 to 27). This finding may be of some consequence with regard to the waste of plant nutrients and irrigation waters. Fingering can also accelerate the contamination of shallow groundwaters.

There were some difficulties associated with the experiment. Because the experiment ran only 1.5 years, it was only possible to attain steady state conditions for a few of the higher LF plots. Because of this time constraint, it was found that the drainage results from the lower leaching treatments may have been biased by unsalinized irrigations previous to experiment startup. The result was that salt-loading estimations may have been lower than expected. Also, the possible consequence of salt build-up from long-term salinized irrigation at LF = 0.05 was not investigated but may be substantial.

It was found that there were 12 instances when treatments having lower LFs and lower CUCs had better plant performances than treatments having higher LFs and higher CUCs (see Chapter IV, rating actual LF x measured CUC x plant performance). These unexpected results may be partially explained by noting that the better performing plots also exhibited higher rates of salt-loading. It is expected that if steady state had been reached, the variability of the plant performances (as a function of ΔT and tissue moisture content) would decrease because the plant and soil-water parameters would have fallen into a wider range of values. As the variability decreases, the number of instances of lower CUC and lower LF treatments having better plant performance would have also been expected to decrease.

Another difficulty with the experiment was the very large effect that wind speed had on CUC values. Both the magnitude and directional changes caused rather large standard deviations and averaged CUC values that were less than desired for the higher uniformity treatments. It was found that 16 CUC analyses are required to estimate the mean CUC within 10% for the low LF and low CUC treatments under these windy conditions.

Finally, we conclude that the development of a saline irrigation plant response model would have to be extremely complex. The model would have to consider the variation in water and salt distribution as influenced by irrigation management, the small spatial scale variation in soil properties and cultural management practices and the plant's ability to integrate soil conditions over both a horizontal and vertical plane. The number of samples required to validate such a model may be high, as indicated by Table 14. However, from an applied perspective, our results indicate that irrigating tall fescue with saline water (2.5 dS m^{-1}) and maintaining the highest possible CUC, enables the LF to be minimized and water savings to occur while still obtaining favorable soil salinities and plant response.

EXHIBITS

TABLES

Table 1.—Results of multiple regression analysis of treatments (N = 9) averaged over the entire experiment

Dependent Variable	R-sqrd	p	Independent Variables
Actual CUC	....	....	No significant correlation
Actual evapotranspiration	0.51	***	Yield
Actual LF	0.84	***	Depth-wgtd EC_e (0 to 45 cm) ‡
Actual LF	0.85	***	Irrigation volume
Canopy temperature (T_c - T_a)	0.65	**	Tissue moisture content
Canopy temperature (T_c - T_a)	0.56	*	Turf yield
Depth-wgtd EC_e (0 to 45 cm) ‡	0.87	***	Irrigation volume
Imposed CUC	0.88	***	Measured CUC
Imposed LF	0.80	***	Actual LF
Irrigation	0.80	***	Actual LF
Irrigation	0.65	**	Depth-wgtd chloride (0 to 45 cm) ‡
Normalized performance †	0.67	**	Depth-wgtd EC_e (0 to 45 cm) ‡
Normalized performance †	0.72	**	Soil gravimetric water content
Tissue moisture content	0.53	*	Actual LF
Tissue moisture content	0.65	**	Canopy temperature
Tissue moisture content	0.76	**	Depth-wgtd EC_e (0 to 45 cm) ‡
Tissue moisture content	0.81	***	Irrigation volume
Yield	0.79	**	Moisture content
Yield	0.57	*	Irrigation volume

Note:

† Sum of normalized canopy temperature & normalized moisture content over last year of experiment

‡ End of experiment data

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

NS = not significant

Table 2.—Soil parameters measured at the beginning of the experiment for LF treatment = 0,05

Parameter	Units	N	Imposed Treatment Values					
			LF = 0,05 CUC = 0,65		LF = 0,05 CUC = 0,75		LF = 0,05 CUC = 0,85	
			Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Soil EC_e (0 to 15 cm) ‡ §	(dS / m)	1	3,0	1,3	2,0	0,8	1,6	0,6
Soil EC_e (15 to 45 cm) ‡ §	(dS / m)	1	3,8	1,0	1,8	1,7	1,3	0,5
Depth-weighted EC_e (0-45 cm) §	(dS / m)	1	3,5	...	1,9	...	1,4	....
Soil Gravimetric w.c. (0 to 15 cm) §	(g water) / (oven-dried soil)	1	0,26	0,12	0,29	0,05	0,21	0,03
Soil Gravimetric w.c. (15 to 45 cm) §	(g water) / (oven-dried soil)	1	0,23	0,06	0,22	0,05	0,20	0,07
Depth-weighted Gravimetric w.c. (0-45 cm) §	(g water) / (oven-dried soil)	1	0,24	....	0,24	...	0,20	....

Notes:

‡ Saturation extract

§ 36 samples per each N sampling event

Table 3.—Soil parameters measured at the beginning of the experiment for LF treatment = 0.15

Parameter	Units	N	Imposed Treatment Values					
			LF = 0.15 CUC = 0.65		LF = 0.15 CUC = 0.75		LF = 0.15 CUC = 0.85	
			Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Soil EC_e (0 to 15 cm) ‡ §	(dS / m)	1	1.4	0.6	1.7	0.7	1.8	0.7
Soil EC_e (15 to 45 cm) ‡ §	(dS / m)	1	1.8	1.8	1.6	1.3	2.0	1.3
Depth-weighted EC_e (0-45 cm) §	(dS / m)	1	1.7	....	1.6	....	1.9	....
Soil Gravimetric w.c. (0 to 15 cm) §	(g water) / (oven-dried soil)	1	0.17	0.03	0.19	0.02	0.25	0.11
Soil Gravimetric w.c. (15 to 45 cm) §	(g water) / (oven-dried soil)	1	0.14	0.04	0.19	0.05	0.22	0.07
Depth-weighted Gravimetric w.c. (0-45 cm) §	(g water) / (oven-dried soil)	1	0.15	....	0.19	....	0.23	....

Notes:

‡ Saturation extract

§ 36 samples per each N sampling event

Table 4.—Soil parameters measured at the beginning of the experiment for LF treatment = 0.25

Parameter	Units	N	Imposed Treatment Values					
			LF = 0.25 CUC = 0.65		LF = 0.25 CUC = 0.75		LF = 0.25 CUC = 0.85	
			Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Soil EC_e (0 to 15 cm) ‡ §	(dS / m)	1	1.5	1.1	2.0	1.2	2.1	1.1
Soil EC_e (15 to 45 cm) ‡ §	(dS / m)	1	1.5	2.0	2.2	1.6	2.5	2.1
Depth-weighted EC_e (0-45 cm) §	(dS / m)	1	1.5	....	2.1	...	2.3	....
Soil Gravimetric w.c. (0 to 15 cm) §	(g water) / (oven-dried soil)	1	0.17	0.03	0.22	0.03	0.22	0.02
Soil Gravimetric w.c. (15 to 45 cm) §	(g water) / (oven-dried soil)	1	0.19	0.07	0.21	0.04	0.20	0.04
Depth-weighted Gravimetric w.c. (0-45 cm) §	(g water) / (oven-dried soil)	1	0.18	...	0.21	....	0.21	....

Notes:

‡ Saturation extract

§ 36 samples per each N sampling event

Table 5.—Soil salinity (as measured by EC_e) before salinization began

Imposed Treatment Values

Depth of Sampling (cm)	LF = 0.05 and CUC = 0.65 (low) CV Avg.	LF = 0.05 and CUC = 0.65 (low) CV Range †	LF = 0.05 and CUC = 0.75 (mid) CV Avg.	LF = 0.05 and CUC = 0.75 (mid) CV Range †	LF = 0.05 and CUC = 0.85 (high) CV Avg.	LF = 0.05 and CUC = 0.85 (high) CV Range †
0 to 15	0.30	(0.24 - 0.36)	0.26	(0.26 - 0.28)	0.25	(0.33 - 0.46)
15 to 45	0.18	(0.15 - 0.20)	0.65	(0.44 - 0.87)	0.24	(0.21 - 0.28)
0 to 45 cm ‡	0.22	....	0.52	....	0.24	....

Depth of Sampling (cm)	LF = 0.15 and CUC = 0.65 (low) CV Avg.	LF = 0.15 and CUC = 0.65 (low) CV Range †	LF = 0.15 and CUC = 0.75 (mid) CV Avg.	LF = 0.15 and CUC = 0.75 (mid) CV Range †	LF = 0.15 and CUC = 0.85 (high) CV Avg.	LF = 0.15 and CUC = 0.85 (high) CV Range †
0 to 15	0.29	(0.26 - 0.30)	0.26	(0.20 - 0.32)	0.25	(0.20 - 0.31)
15 to 45	0.73	(0.47 - 0.98)	0.56	(0.52 - 0.61)	0.45	(0.42 - 0.48)
0 to 45 cm ‡	0.58	....	0.46	....	0.38	....

Depth of Sampling (cm)	LF = 0.25 and CUC = 0.65 (low) CV Avg.	LF = 0.25 and CUC = 0.65 (low) CV Range †	LF = 0.25 and CUC = 0.75 (mid) CV Avg.	LF = 0.25 and CUC = 0.75 (mid) CV Range †	LF = 0.25 and CUC = 0.85 (high) CV Avg.	LF = 0.25 and CUC = 0.85 (high) CV Range †
0 to 15	0.50	(0.46 - 0.54)	0.36	(0.25 - 0.46)	0.38	(0.37 - 0.39)
15 to 45	0.80	(0.75 - 0.86)	0.55	(0.39 - 0.72)	0.60	(0.55 - 0.64)
0 to 45 ‡	0.70	....	0.49	....	0.53	....

Notes:

† Ranges are provided instead of standard deviation because there were only 2 samples

‡ The 0 to 15 cm data are weighted 1/3 while the 15 to 45 cm data are weighted 2/3

Table 6.—Average values of plant and soil parameters measured over the last year of the experiment for LF treatment = 0.05

Parameter	Units	N	Imposed Treatment Values					
			LF = 0.05 CUC = 0.65		LF = 0.05 CUC = 0.75		LF = 0.05 CUC = 0.85	
			Avg.	Std. dev. †	Avg.	Std. dev. †	Avg.	Std. dev. †
Canopy Temperature (T_c - T_a) ††	(degrees Celsius)	24	3.9	19.6	2.3	13.8	1.7	10.8
Tissue Moisture Content §§	(g water) / (g fresh tissue)	12	0.55	0.17	0.63	0.11	0.62	0.11
Turf Yield §§	(g) / ((plot area) (week))	52	810	1198	1528	1375	1391	1320
Soil EC_e (0 to 15 cm) ‡ §	(dS / m)	2	10.1	11.9	7.1	8.4	4.8	4.9
Soil EC_e (15 to 45 cm) ‡ §	(dS / m)	2	10.5	10.3	8.1	9.0	7.3	7.5
Depth-weighted EC_e (0-45 cm) §	(dS / m)	2	10.4	....	7.8	....	6.4	....
Soil Gravimetric w.c. (0 to 15 cm) §	(g water) / (oven-dried soil)	2	0.22	0.05	0.19	0.04	0.20	0.04
Soil Gravimetric w.c. (15 to 45 cm) §	(g water) / (oven-dried soil)	2	0.21	0.06	0.15	0.07	0.16	0.09
Depth-weighted Gravimetric w.c. (0-45 cm) §	(g water) / (oven-dried soil)	2	0.21	....	0.17	....	0.18	....
Soil Chloride (0 to 15 cm) ‡ § ‡‡	(meq / liter)	1	169	140	99	113	63	49
Soil Chloride (15 to 45 cm) ‡ § ‡‡	(meq / liter)	1	147	120	119	111	116	84
Depth-weighted Chloride (0-45 cm) § ‡‡	(meq / liter)	1	155	....	113	....	98	....

Notes:

† Std. Dev. Of averaged treatment is the square root of the sum of squares of each treatment.

‡ Saturation extract

†† 25 samples per each N sampling event

§ 36 samples per each N sampling event

§§ 1 sample per each N sampling event

‡‡ End of experiment data

Table 7.—Average values of plant and soil parameters measured over the last year of the experiment for LF treatment = 0.15

			Imposed Treatment Values					
			LF = 0.15 CUC = 0.65		LF = 0.15 CUC = 0.75		LF = 0.15 CUC = 0.85	
Parameter	Units	N	Avg.	Std. dev. †	Avg.	Std. dev. †	Avg.	Std. dev. †
Canopy Temperature (T_c - T_a) ††	(degrees Celsius)	24	1.8	16.1	2.3	13.9	1.7	11.0
Tissue Moisture Content §§	(g water) / (g fresh tissue)	12	0.61	0.10	0.63	0.11	0.65	0.1
Turf Yield §§	(g) / ((plot area) (week))	52	1155	1290	1408	1250	1888	1871
Soil EC_e (0 to 15 cm) ‡ §	(dS / m)	2	8.2	9.1	6.8	8.6	5.3	4.1
Soil EC_e (15 to 45 cm) ‡ §	(dS / m)	2	7.6	8.3	7.0	6.6	6.9	5.2
Depth-weighted EC_e (0-45 cm) §	(dS / m)	2	7.8	....	6.9	....	6.3	...
Soil Gravimetric w.c. (0 to 15 cm) §	(g water) / (oven-dried soil)	2	0.18	0.06	0.21	0.05	0.21	0.04
Soil Gravimetric w.c. (15 to 45 cm) §	(g water) / (oven-dried soil)	2	0.14	0.05	0.18	0.08	0.18	0.05
Depth-weighted Gravimetric w.c. (0-45 cm) §	(g water) / (oven-dried soil)	2	0.15	...	0.19	....	0.19	...
Soil Chloride (0 to 15 cm) ‡ § ‡‡	(meq / liter)	1	102	101	104	82	74	37
Soil Chloride (15 to 45 cm) ‡ § ‡‡	(meq / liter)	1	81	63	106	69	97	49
Depth-weighted Chloride (0-45 cm) § ‡‡	(meq / liter)	1	88	...	105	....	89	....

Notes:

† Std. Dev. Of averaged treatment is the square root of the sum of squares of each treatment.

‡ Saturation extract

†† 25 samples per each N sampling event

§ 36 samples per each N sampling event

§§ 1 sample per each N sampling event

‡‡ End of experiment data

Table 8.—Average values of plant and soil parameters measured over the last year of the experiment for LF treatment = 0.25

Parameter	Units	N	Imposed Treatment Values: LF = 0.25, CUC = 0.65 Avg.	Std. dev. †	LF = 0.25, CUC = 0.75 Avg.	Std. dev. †	LF = 0.25, CUC = 0.85 Avg.	Std. dev. †
Canopy Temperature (T_c - T_a) ††	(degrees Celsius)	24	1.6	14.4	2.4	10.0	1.8	11.6
Tissue Moisture Content §§	(g water) / (g fresh tissue)	12	0.65	0.09	0.62	0.11	0.64	0.11
Turf Yield §§	(g) / ((plot area) (week))	52	2000	1748	1138	956	1354	1413
Soil EC_e (0 to 15 cm) ‡ §	(dS / m)	2	6.1	8.4	4.7	2.3	5.1	2.7
Soil EC_e (15 to 45 cm) ‡ §	(dS / m)	2	6.2	9.1	4.7	3.4	5.1	3.4
Depth-weighted EC_e (0-45 cm) §	(dS / m)	2	6.2	....	4.7	...	5.1	....
Soil Gravimetric w.c. (0 to 15 cm) §	(g water) / (oven-dried soil)	2	0.20	0.05	0.23	0.04	0.22	0.04
Soil Gravimetric w.c. (15 to 45 cm) §	(g water) / (oven-dried soil)	2	0.20	0.07	0.21	0.05	0.19	0.06
Depth-weighted Gravimetric w.c. (0-45 cm) §	(g water) / (oven-dried soil)	2	0.20	....	0.22	....	0.20	...
Soil Chloride (0 to 15 cm) ‡ § ‡‡	(meq / liter)	1	85	95	55	21	65	28
Soil Chloride (15 to 45 cm) ‡ § ‡‡	(meq / liter)	1	80	95	49	27	62	28
Depth-weighted Chloride (0-45 cm) § ‡‡	(meq / liter)	1	82		51		63	

Notes:

† Std. Dev. Of averaged treatment is the square root of the sum of squares of each treatment.

‡ Saturation extract

†† 25 samples per each N sampling event

§ 36 samples per each N sampling event

§§ 1 sample per each N sampling event

‡‡ End of experiment data

Table 9.—Plant and soil parameters measured at the end of the experiment for LF treatment = 0.05

Parameter	Units	N	Imposed Treatment Values					
			LF = 0.05 CUC = 0.65		LF = 0.05 CUC = 0.75		LF = 0.05 CUC = 0.85	
			Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Canopy Temperature (T_c - T_a) ††	(degrees Celsius)	1	-0.18	1.95	-0.82	1.49	-2.08	1.32
Tissue Moisture Content §§	(g water) / (g fresh tissue)	1	0.63	....	0.64	....	0.64	....
Turf Yield §§	(g) / ((plot area) (week))	1	1619	....	1973	....	1769	....
Soil EC_e (0 to 15 cm) ‡ §	(dS / m)	1	16.1	11.9	10.3	8.3	6.9	4.8
Soil EC_e (15 to 45 cm) ‡ §	(dS / m)	1	15.7	9.9	12.3	8.6	11.7	7.4
Depth-weighted EC_e (0-45 cm) §	(dS / m)	1	15.9	....	11.6	....	10.1	....
Soil Gravimetric w.c. (0 to 15 cm) §	(g water) / (oven-dried soil)	1	0.21	0.04	0.19	0.03	0.21	0.02
Soil Gravimetric w.c. (15 to 45 cm) §	(g water) / (oven-dried soil)	1	0.20	0.05	0.16	0.04	0.18	0.06
Depth-weighted Gravimetric w.c. (0-45 cm) §	(g water) / (oven-dried soil)	1	0.20	....	0.17	....	0.19	....
Soil Chloride (0 to 15 cm) ‡ § ‡‡	(meq / liter)	1	169	140	99	113	63	49
Soil Chloride (15 to 45 cm) ‡ § ‡‡	(meq / liter)	1	147	120	119	111	116	84
Depth-weighted Chloride (0-45 cm) § ‡‡	(meq / liter)	1	155	....	113	....	98	....

Notes:

‡ Saturation extract

†† 25 samples per each N sampling event

§ 36 samples per each N sampling event

§§ 1 sample per each N sampling event

‡‡ End of experiment data

Table 10.—Plant and soil parameters measured at the end of the experiment for LF treatment = 0.15

Parameter	Units	N	Imposed Treatment Values					
			LF = 0.15 CUC = 0.65		LF = 0.15 CUC = 0.75		LF = 0.15 CUC = 0.85	
			Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Canopy Temperature (T_c - T_a) ††	(degrees Celsius)	1	-1.09	1.68	-1.29	1.62	-1.43	1.21
Tissue Moisture Content §§	(g water) / (g fresh tissue)	1	0.65	....	0.65	....	0.68	....
Turf Yield §§	(g) / ((plot area) (week))	1	1544	....	1676	....	3288	....
Soil EC_e (0 to 15 cm) ‡ §	(dS / m)	1	12.8	9.0	9.8	8.5	7.6	4.1
Soil EC_e (15 to 45 cm) ‡ §	(dS / m)	1	12.0	7.9	10.2	6.0	10.2	4.9
Depth-weighted EC_e (0-45 cm) §	(dS / m)	1	12.3	....	10.1	....	9.3	....
Soil Gravimetric w.c. (0 to 15 cm) §	(g water) / (oven-dried soil)	1	0.17	0.04	0.21	0.03	0.22	0.03
Soil Gravimetric w.c. (15 to 45 cm) §	(g water) / (oven-dried soil)	1	0.12	0.03	0.19	0.05	0.20	0.04
Depth-weighted Gravimetric w.c. (0-45 cm) §	(g water) / (oven-dried soil)	1	0.14	....	0.20	....	0.21	....
Soil Chloride (0 to 15 cm) ‡ § ‡‡	(meq / liter)	1	102	101	104	82	74	37
Soil Chloride (15 to 45 cm) ‡ § ‡‡	(meq / liter)	1	81	63	106	69	97	49
Depth-weighted Chloride (0-45 cm) § ‡‡	(meq / liter)	1	88	....	105	....	89	....

Notes:

‡ Saturation extract

†† 25 samples per each N sampling event

§ 36 samples per each N sampling event

§§ 1 sample per each N sampling event

‡‡ End of experiment data

Table 11.—Plant and soil parameters measured at the end of the experiment for LF treatment = 0.25

Parameter	Units	N	Imposed Treatment Values: LF = 0.25, CUC = 0.65 Avg.	Std. dev.	LF = 0.25, CUC = 0.75 Avg.	Std. dev.	LF = 0.25, CUC = 0.85 Avg.	Std. dev.
Canopy Temperature (T_c - T_a) ††	(degrees Celsius)	1	-1.22	1.42	-1.42	1.39	-1.63	1.09
Tissue Moisture Content §§	(g water) / (g fresh tissue)	1	0.67	....	0.60	....	0.61	....
Turf Yield §§	(g) / ((plot area) (week))	1	2778	....	1232	....	1483	....
Soil EC_e (0 to 15 cm) ‡ §	(dS / m)	1	8.6	8.3	6.0	2.1	6.9	2.7
Soil EC_e (15 to 45 cm) ‡ §	(dS / m)	1	8.4	8.5	5.9	3.1	7.1	3.0
Depth-weighted EC_e (0-45 cm) §	(dS / m)	1	8.4	....	6.0	....	7.0	....
Soil Gravimetric w.c. (0 to 15 cm) §	(g water) / (oven-dried soil)	1	0.19	0.04	0.23	0.03	0.21	0.03
Soil Gravimetric w.c. (15 to 45 cm) §	(g water) / (oven-dried soil)	1	0.19	0.05	0.21	0.03	0.19	0.05
Depth-weighted Gravimetric w.c. (0-45 cm) §	(g water) / (oven-dried soil)	1	0.19	....	0.22	....	0.20	....
Soil Chloride (0 to 15 cm) ‡ § ‡‡	(meq / liter)	1	85	95	55	21	65	28
Soil Chloride (15 to 45 cm) ‡ § ‡‡	(meq / liter)	1	80	95	49	27	62	28
Depth-weighted Chloride (0-45 cm) § ‡‡	(meq / liter)	1	82		51		63	

Notes:

‡ Saturation extract

†† 25 samples per each N sampling event

§ 36 samples per each N sampling event

§§ 1 sample per each N sampling event

‡‡ End of experiment data

Table 12.—Statistical significance for effects of LF and CUC

		Significance				
Source of Variation	df	Depth-weighted soil salinity	Soil gravimetric water content	Canopy temperature	Tissue moisture content	Yield
LF	2	***	NS	***	***	**
CUC	2	***	NS	***	***	***
LF x CUC	4	***	NS	***	***	***

Note:
*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
NS = not significant

Table 13.—Soil salinity (as measured by EC_e) coefficients of variation and Spearman rank correlations that correlate sampling data at 1 year and 1½ years after salinization began

Imposed Treatment Values

Depth of Sampling (cm)	LF = 0.05 and CUC = 0.65 (low)				LF = 0.05 and CUC = 0.75 (mid)				LF = 0.05 and CUC = 0.85 (high)			
	CV		Rank correlations		CV		Rank correlations		CV		Rank correlations	
	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡
0 to 15	0.36	0.14	0.43	(0.37 - 0.49)	0.40	0.19	0.34	(0.26 - 0.43)	0.34	0.13	0.13	(-0.02 - 0.28)
15 to 45	0.38	0.08	0.47	(0.37 - 0.49)	0.49	0.08	0.49	(0.43 - 0.54)	0.40	0.08	0.27	(0.25 - 0.30)
0 to 45 §	0.37	....	0.46	....	0.46	....	0.44	....	0.38	....	0.22	....

Depth of Sampling (cm)	LF = 0.15 and CUC = 0.65 (low)				LF = 0.15 and CUC = 0.75 (mid)				LF = 0.15 and CUC = 0.85 (high)			
	CV		Rank correlations		CV		Rank correlations		CV		Rank correlations	
	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡
0 to 15	0.36	0.13	0.27	(0.09 - 0.45)	0.41	0.21	0.39	(0.15 - 0.63)	0.29	0.08	-0.23	(-0.49 - 0.04)
15 to 45	0.46	0.07	0.48	(0.35 - 0.60)	0.44	0.09	0.43	(0.18 - 0.67)	0.33	0.06	0.43	(0.36 - 0.49)
0 to 45 §	0.43	....	0.41	....	0.43	....	0.42	....	0.31	....	0.21	....

Depth of Sampling (cm)	LF = 0.25 and CUC = 0.65 (low)				LF = 0.25 and CUC = 0.75 (mid)				LF = 0.25 and CUC = 0.85 (high)			
	CV		Rank correlations		CV		Rank correlations		CV		Rank correlations	
	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡
0 to 15	0.41	0.21	0.45	(0.22 - 0.69)	0.23	0.01	0.08	(-0.25 - 0.41)	0.20	0.07	0.25	(0.06 - 0.44)
15 to 45	0.66	0.07	0.46	(0.16 - 0.77)	0.31	0.06	0.46	(0.44 - 0.47)	0.30	0.10	0.39	(0.06 - 0.72)
0 to 45 §	0.58	....	0.46	....	0.28	....	0.33	....	0.27	....	0.34	....

Notes:

† N = 4 for each sampling interval, two treatments at the 1 year sampling event and two treatments at the 1½ year sampling event

‡ Ranges are provided instead of standard deviation because there were only 2 samples

§ The 0 to 15 cm data are weighted 1/3 while the 15 to 45 cm data are weighted 2/3

Table 14.—Number of samples required to estimate the mean within 10% at the 95% confidence level

Soil Salinity (as EC)

CUC	LF = 0.05		LF = 0.15		LF = 0.25	
	Sample depth 0 to 15 cm	Sample depth 15 to 45 cm	Sample depth 0 to 15 cm	Sample depth 15 to 45 cm	Sample depth 0 to 15 cm	Sample depth 15 to 45 cm
0.65 (low)	108	81	102	93	167	216
0.75 (mid)	141	158	165	81	22	42
0.85 (high)	98	88	56	52	30	44

Soil Gravimetric Water Content

CUC	LF = 0.05		LF = 0.15		LF = 0.25	
	Sample depth 0 to 15 cm	Sample depth 15 to 45 cm	Sample depth 0 to 15 cm	Sample depth 15 to 45 cm	Sample depth 0 to 15 cm	Sample depth 15 to 45 cm
0.65 (low)	8	15	6	11	4	17
0.75 (mid)	4	16	5	16	3	5
0.85 (high)	4	22	6	8	3	18

Canopy Temperature

CUC	LF = 0.05	LF = 0.15	LF = 0.25
0.65 (low)	5	4	3
0.75 (mid)	2	3	1
0.85 (high)	1	1	1

Moisture Content

CUC	LF = 0.05	LF = 0.15	LF = 0.25
0.65 (low)	2	2	1
0.75 (mid)	2	1	2
0.85 (high)	1	1	1

Note: LFs and CUCs are imposed treatment values

Table 15.—Results of multiple regression analysis of treatments (N = 18) averaged over the entire experiment

Dependent Variable	R-sqrd	p	Independent Variables
Actual CUC	0.27	*	EC_e (0 to 15 cm) ‡
Actual evapotranspiration	0.33	*	Turf Yield
Actual LF	0.59	***	Irrigation volume
Canopy temperature (T_c - T_a)	0.23	*	Actual LF
Canopy temperature (T_c - T_a)	0.24	*	Tissue moisture content
Depth-wgtd EC_e (0 to 45 cm) ‡	0.76	***	Irrigation volume
Imposed CUC	0.77	***	Measured CUC
Imposed LF	0.85	***	Actual LF
Irrigation	0.76	***	Depth-wgtd EC_e (0 to 45 cm) ‡
Normalized performance †		*	Turf Yield
Tissue moisture content	0.48	**	Actual LF
Tissue moisture content	0.60	***	Irrigation
Tissue moisture content	0.70	***	Yield
Tissue moisture content	0.80	***	Irrigation **, Yield ***
Yield	0.33	*	Depth-wgtd EC_e (0 to 45 cm) ‡
Yield	0.45	**	Irrigation Volume

Note:

† Sum of normalized canopy temperature & normalized moisture content over last year of experiment

‡ End of experiment data

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

NS = not significant

Table 16.—Yield as a function of ambient temperature

Sampling interval	Average Temperature (Celcius)	Imposed LF = 0.05 Average weekly turf yield (grams)	Imposed LF = 0.25 Average weekly turf yield (grams)	Percent Difference
October - March	11	722	820	12%
April - September	26	1056	1342	21%
July - August	32	994	1424	30%

Table 17.—Canopy temperature and tissue moisture content coefficients of variation and Spearman rank correlations that correlate with the preceding sampling event

Imposed Treatment Values

Parameter	LF = 0.05 and CUC = 0.65 (low)				LF = 0.05 and CUC = 0.75 (mid)				LF = 0.05 and CUC = 0.85 (high)			
	CV		Rank correlations †		CV		Rank correlations †		CV		Rank correlations †	
	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Canopy temperature (T_c - Ta) ‡	0.08	0.06	0.35	0.44	0.06	0.02	0.15	0.38	0.05	0.02	0.11	0.35
Tissue Moisture Content §	0.08	0.03	0.41	0.32	0.05	0.04	0.33	0.38	0.04	0.02	0.33	0.30

Parameter	LF = 0.15 and CUC = 0.65 (low)				LF = 0.15 and CUC = 0.75 (mid)				LF = 0.15 and CUC = 0.85 (high)			
	CV		Rank correlations †		CV		Rank correlations †		CV		Rank correlations †	
	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Canopy temperature (T_c - Ta) ‡	0.06	0.03	0.27	0.43	0.06	0.03	0.11	0.42	0.06	0.03	0.12	0.36
Tissue Moisture Content §	0.05	0.03	0.26	0.42	0.05	0.02	0.26	0.31	0.05	0.05	0.22	0.35

Parameter	LF = 0.25 and CUC = 0.65 (low)				LF = 0.25 and CUC = 0.75 (mid)				LF = 0.25 and CUC = 0.85 (high)			
	CV		Rank correlations †		CV		Rank correlations †		CV		Rank correlations †	
	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.	Avg.	Std. dev.
Canopy temperature (T_c - Ta) ‡	0.06	0.03	0.16	0.35	0.05	0.02	0.10	0.34	0.05	0.02	0.10	0.37
Tissue Moisture Content §	0.05	0.03	0.36	0.35	0.05	0.04	0.30	0.26	0.06	0.04	0.40	0.33

Notes:

† Spearman rank correlation

‡ Canopy temperatures (measured), (n = 26 for CV, and n = 25 for Spearman rank correlation)

§ Tissue moisture content, (n = 13 for CV, and n = 12 for Spearman rank correlation)

Table 18.—Soil gravimetric water content coefficients of variation before salinization began

Imposed Treatment Values

Depth of Sampling (cm)	LF = 0.05 and CUC = 0.65 (low) CV		LF = 0.05 and CUC = 0.75 (mid) CV		LF = 0.05 and CUC = 0.85 (high) CV	
	Avg.	Range †	Avg.	Range †	Avg.	Range †
0 to 15	0.29	(0.09 - 0.41)	0.09	(0.07 - 0.12)	0.12	(0.11 - 0.13)
15 to 45	0.17	(0.11 - 0.23)	0.15	(0.14 - 0.16)	0.24	(0.12 - 0.37)
0 to 45 §	0.21	....	0.13	....	0.20	....

Depth of Sampling (cm)	LF = 0.15 and CUC = 0.65 (low) CV		LF = 0.15 and CUC = 0.75 (mid) CV		LF = 0.15 and CUC = 0.85 (high) CV	
	Avg.	Range †	Avg.	Range †	Avg.	Range †
0 to 15	0.12	(0.11 - 0.13)	0.08	(0.07 - 0.08)	0.32	(0.31 - 0.32)
15 to 45	0.18	(0.15 - 0.22)	0.19	(0.12 - 0.25)	0.22	(0.22 - 0.23)
0 to 45 §	0.16	....	0.15	....	0.25	....

Depth of Sampling (cm)	LF = 0.25 and CUC = 0.65 (low) CV		LF = 0.25 and CUC = 0.75 (mid) CV		LF = 0.25 and CUC = 0.85 (high) CV	
	Avg.	Range †	Avg.	Range †	Avg.	Range †
0 to 15	0.13	(0.11 - 0.15)	0.08	(0.06 - 0.10)	0.07	(0.05 - 0.09)
15 to 45	0.24	(0.18 - 0.30)	0.12	(0.07 - 0.17)	0.11	(0.08 - 0.14)
0 to 45 §	0.20	....	0.11	....	0.10	....

Notes:

† Ranges are provided instead of standard deviation because there were only 2 samples

‡ The 0 to 15 cm data are weighted 1/3 while the 15 to 45 cm data are weighted 2/3

Table 19.—Soil gravimetric water content coefficients of variation and Spearman rank correlations that correlate sampling data at 1 year and 1½ years after salinization began

Imposed Treatment Values

Depth of Sampling (cm)	LF = 0.05 and CUC = 0.65 (low)				LF = 0.05 and CUC = 0.75 (mid)				LF = 0.05 and CUC = 0.85 (high)			
	CV		Rank correlations		CV		Rank correlations		CV		Rank correlations	
	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡
0 to 15	0.11	0.04	0.67	(0.59 - 0.74)	0.11	0.02	0.63	(0.54 - 0.71)	0.10	0.04	0.56	(0.44 - 0.68)
15 to 45	0.15	0.05	0.53	(0.50 - 0.55)	0.21	0.05	0.79	(0.73 - 0.85)	0.26	0.07	0.78	(0.73 - 0.83)
0 to 45 §	0.14	....	0.58	....	0.18	....	0.74	....	0.21	....	0.71	....

Depth of Sampling (cm)	LF = 0.15 and CUC = 0.65 (low)				LF = 0.15 and CUC = 0.75 (mid)				LF = 0.15 and CUC = 0.85 (high)			
	CV		Rank correlations		CV		Rank correlations		CV		Rank correlations	
	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡
0 to 15	0.16	0.01	0.73	(0.66 - 0.80)	0.11	0.01	0.67	(0.57 - 0.77)	0.10	0.02	0.57	(0.57 - 0.57)
15 to 45	0.19	0.04	0.66	(0.52 - 0.80)	0.21	0.03	0.83	(0.82 - 0.84)	0.15	0.02	0.70	(0.69 - 0.70)
0 to 45 §	0.18	....	0.68	....	0.18	....	0.78	....	0.13	....	0.66	....

Depth of Sampling (cm)	LF = 0.25 and CUC = 0.65 (low)				LF = 0.25 and CUC = 0.75 (mid)				LF = 0.25 and CUC = 0.85 (high)			
	CV		Rank correlations		CV		Rank correlations		CV		Rank correlations	
	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡	Avg.	Std. dev.†	Avg.	Range ‡
0 to 15	0.11	0.03	0.57	(0.50 - 0.63)	0.09	0.02	0.63	(0.62 - 0.63)	0.09	0.01	0.56	(0.55 - 0.56)
15 to 45	0.19	0.04	0.74	(0.71 - 0.77)	0.11	0.01	0.67	(0.59 - 0.74)	0.18	0.06	0.69	(0.65 - 0.73)
0 to 45 §	0.16	....	0.68	....	0.10	....	0.66	....	0.15	....	0.65	....

Notes:

† N = 4 for each sampling interval, two treatments at the 1 year sampling event and two treatments at the 1½ year sampling event

‡ Ranges are provided instead of standard deviation because there were only 2 samples

§ The 0 to 15 cm data is weighted 1/3 while the 15 to 45 cm data is weighted 2/3

Table 20.—Plant performance, I/ET_o, salt loading and water savings parameters over the duration and at the end of the experiment

Parameter	Units	LF = 0.05 and CUC = 0.65 Avg. ††	LF = 0.05 and CUC = 0.65 At end of experiment	LF = 0.05 and CUC = 0.75 Avg. ††	LF = 0.05 and CUC = 0.75 At end of experiment	LF = 0.05 and CUC = 0.85 Avg. ††	LF = 0.05 and CUC = 0.85 At end of experiment
Plant Performance	†	0.00	0.00	0.71	0.21	0.90	1.00
I/ET_o	§	0.20	0.50	0.61	0.77	0.72	0.78
Salinity ‡	(dS/m)	10.4	15.9	7.8	11.6	6.4	10.1
Water Savings	(cm / yr)	69	109	48	54	27	48

Parameter		LF = 0.15 and CUC = 0.65 Avg. ††	LF = 0.15 and CUC = 0.65 At end of experiment	LF = 0.15 and CUC = 0.75 Avg. ††	LF = 0.15 and CUC = 0.75 At end of experiment	LF = 0.15 and CUC = 0.85 Avg. ††	LF = 0.15 and CUC = 0.85 At end of experiment
Plant Performance	†	0.65	0.18	0.70	0.60	1.00	0.71
I/ET_o	§	0.58	0.78	0.73	0.90	0.81	0.64
Salinity ‡	(dS/m)	7.8	12.3	6.9	10.1	6.3	9.3
Water Savings	(cm / yr)	54	61	27	36	9	77

Parameter		LF = 0.25 and CUC = 0.65 Avg. ††	LF = 0.25 and CUC = 0.65 At end of experiment	LF = 0.25 and CUC = 0.75 Avg. ††	LF = 0.25 and CUC = 0.75 At end of experiment	LF = 0.25 and CUC = 0.85 Avg. ††	LF = 0.25 and CUC = 0.85 At end of experiment
Plant Performance	†	0.97	0.62	0.78	0.50	0.94	0.50
I/ET_o	§	0.85	0.84	0.82	0.98	0.85	0.73
Salinity ‡	(dS/m)	6.2	8.4	4.7	6.0	5.1	7.0
Water Savings	(cm / yr)	1	35	6	0	0	39

Notes:

† Normalization of the summation: (normalized delta canopy temperature + normalized tissue moisture content)

‡ Depth-weighted soil salinity (0 to 45 cm)

Concentration of salts in measured indirectly by EC

§ (cm water) / (cm water)

†† Plant performance is averaged over last 12 months of experiment, all other parameters are average over entire 18 months

Table 21.—Soil saturation extract EC_e coefficients of variation and Spearman rank correlations that correlate with the overlying sampling intervals

Imposed Treatment Values

Depth of Sampling (cm)	LF = 0.05 and CUC = 0.65 (low)		LF = 0.05 and CUC = 0.75 (mid)		LF = 0.05 and CUC = 0.85 (high)	
	CV	Rank correlation †	CV	Rank correlation †	CV	Rank correlation †
0 to 15	0.51	....	0.45	....	0.50	....
15 to 45	0.46	0.07	0.38	0.83	0.40	0.84
75 to 90	0.40	0.00	0.40	0.27	0.33	0.35
165 to 180	0.66	0.63	0.36	0.29	0.28	0.08
0 to 45 ‡	0.48	....	0.40	....	0.43	....
0 to 180 §	0.49	....	0.39	....	0.35	....

Depth of Sampling (cm)	LF = 0.25 and CUC = 0.65 (low)		LF = 0.25 and CUC = 0.75 (mid)		LF = 0.25 and CUC = 0.85 (high)	
	CV	Rank correlation †	CV	Rank correlation †	CV	Rank correlation †
0 to 15	0.66	....	0.23	....	0.26	....
15 to 45	0.66	0.96	0.23	0.25	0.20	0.68
75 to 90	0.56	0.75	0.28	0.49	0.26	0.22
165 to 180	0.55	0.74	0.18	0.44	0.21	0.34
0 to 45 ‡	0.66	....	0.23	....	0.22	....
0 to 180 §	0.59	....	0.23	....	0.23	....

Notes:

† Spearman rank correlation

‡ The 0 to 15 cm data are weighted 1/3 while the 15 to 45 cm data are weighted 2/3

§ The (0 to 15) cm data are weighted 1/12, (15 to 45) are weighted 3/12, (75 to 90) are weighted 5/12, (165 to 180) are weighted 3/12

Table 22.—Soil saturation extract chloride concentration coefficients of variation and Spearman rank correlations that correlate with the overlying sampling intervals

Imposed Treatment Values

Depth of Sampling (cm)	LF = 0.05 and CUC = 0.65 (low)		LF = 0.05 and CUC = 0.75 (mid)		LF = 0.05 and CUC = 0.85 (high)	
	CV	Rank correlation †	CV	Rank correlation †	CV	Rank correlation †
0 to 15	0.58	....	0.51	....	0.56	....
15 to 45	0.58	0.92	0.40	0.78	0.46	0.82
75 to 90	0.54	0.49	0.45	0.35	0.33	0.36
165 to 180	0.81	0.07	0.51	-0.10	0.81	-0.31
0 to 45 ‡	0.58	....	0.44	....	0.50	....
0 to 180 §	0.62	....	0.46	....	0.50	....

Depth of Sampling (cm)	LF = 0.25 and CUC = 0.65 (low)		LF = 0.25 and CUC = 0.75 (mid)		LF = 0.25 and CUC = 0.85 (high)	
	CV	Rank correlation †	CV	Rank correlation †	CV	Rank correlation †
0 to 15	0.76	....	0.18	....	0.28	....
15 to 45	0.74	0.96	0.26	0.59	0.24	0.70
75 to 90	0.56	0.74	0.35	0.49	0.30	0.41
165 to 180	0.64	0.40	0.34	0.23	0.28	0.56
0 to 45 ‡	0.75	....	0.23	....	0.25	....
0 to 180 §	0.64	....	0.31	....	0.28	....

Notes:

† Spearman rank correlation

‡ The 0 to 15 cm data are weighted 1/3 while the 15 to 45 cm data are weighted 2/3

§ The (0 to 15) cm data are weighted 1/12, (15 to 45) are weighted 3/12, (75 to 90) are weighted 5/12, (165 to 180) are weighted 3/12

EXHIBITS

FIGURES

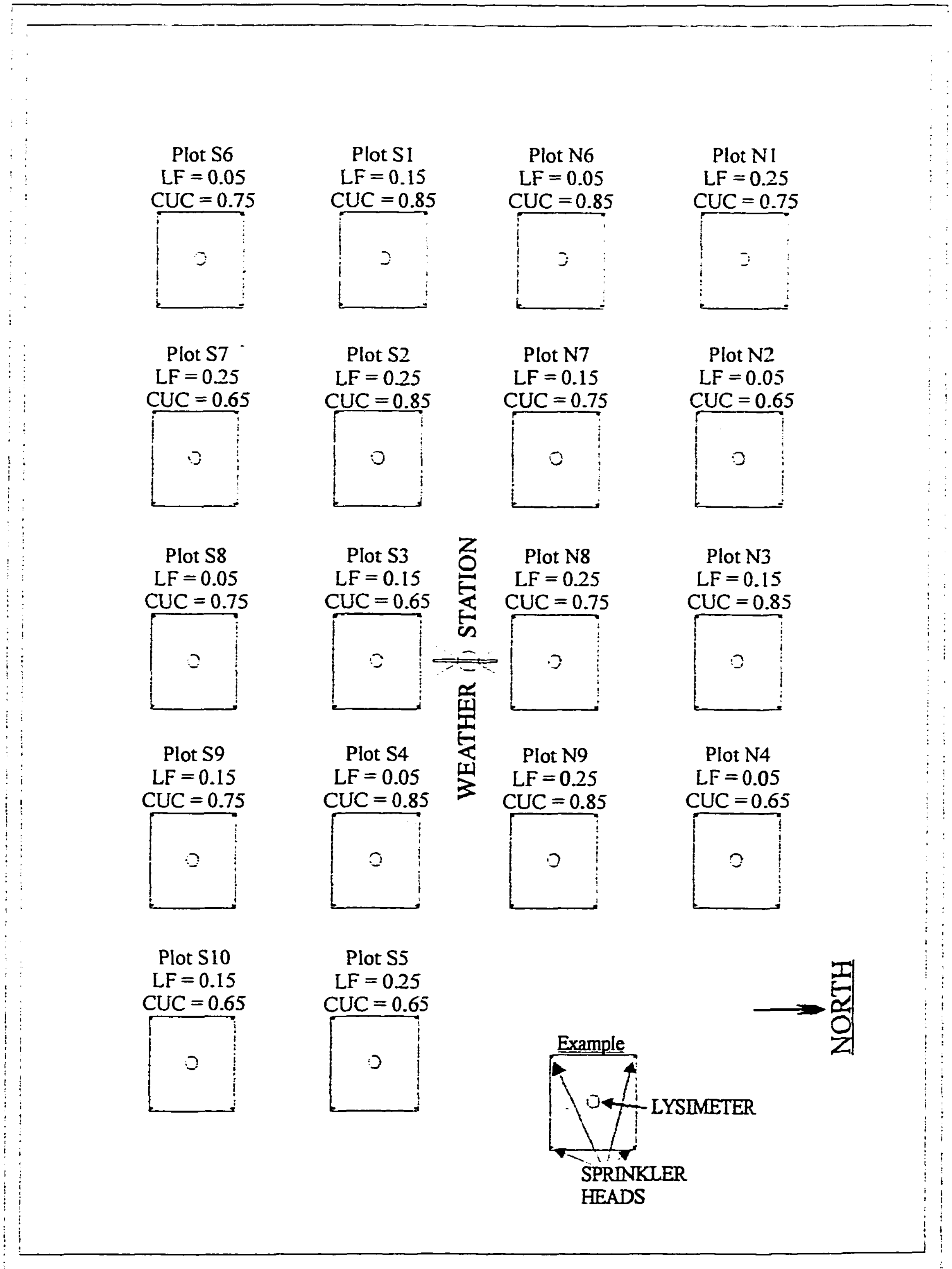

Fig. 1. Site Design with imposed LFs and CUCs

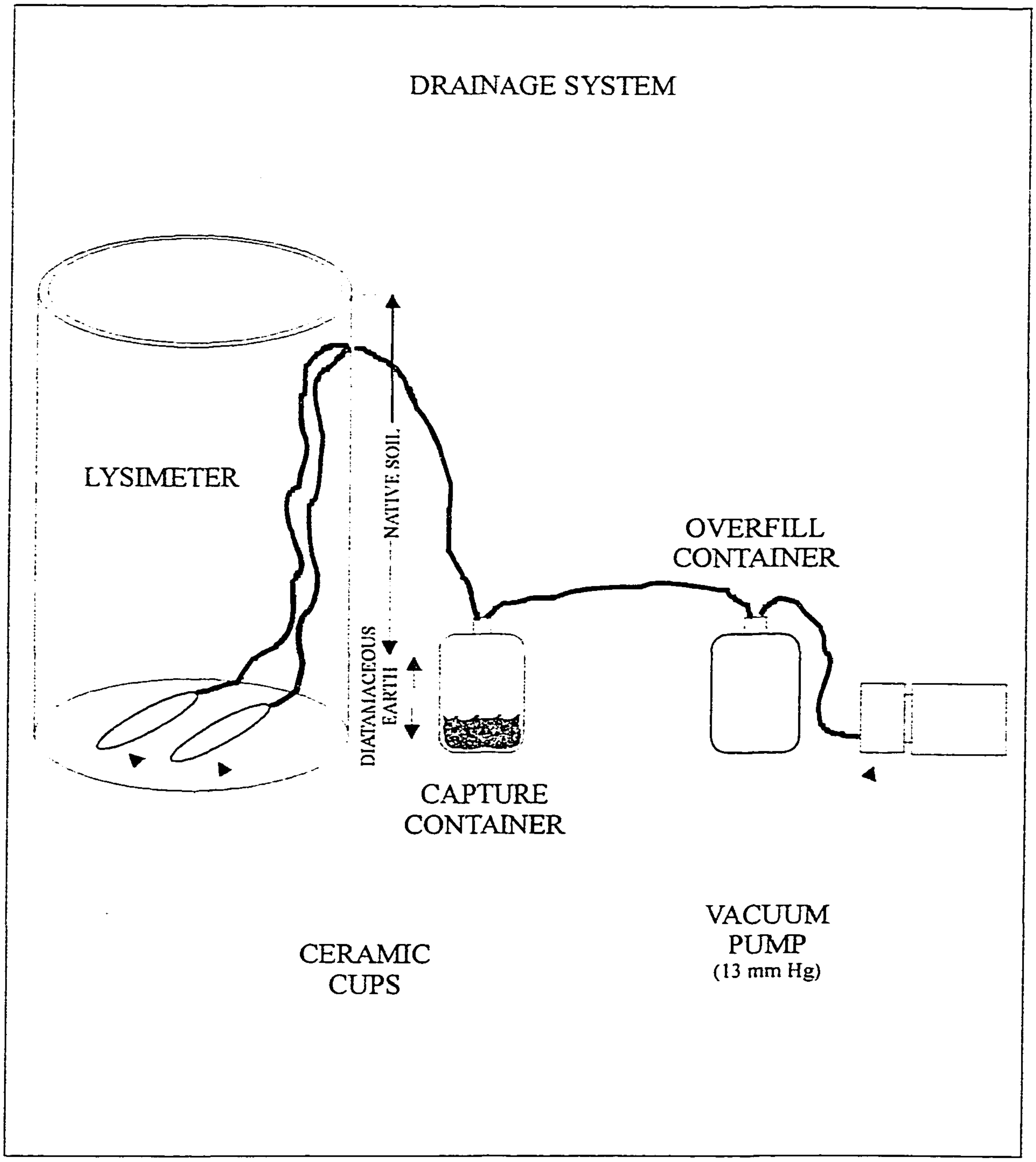

Fig. 2. Drainage system

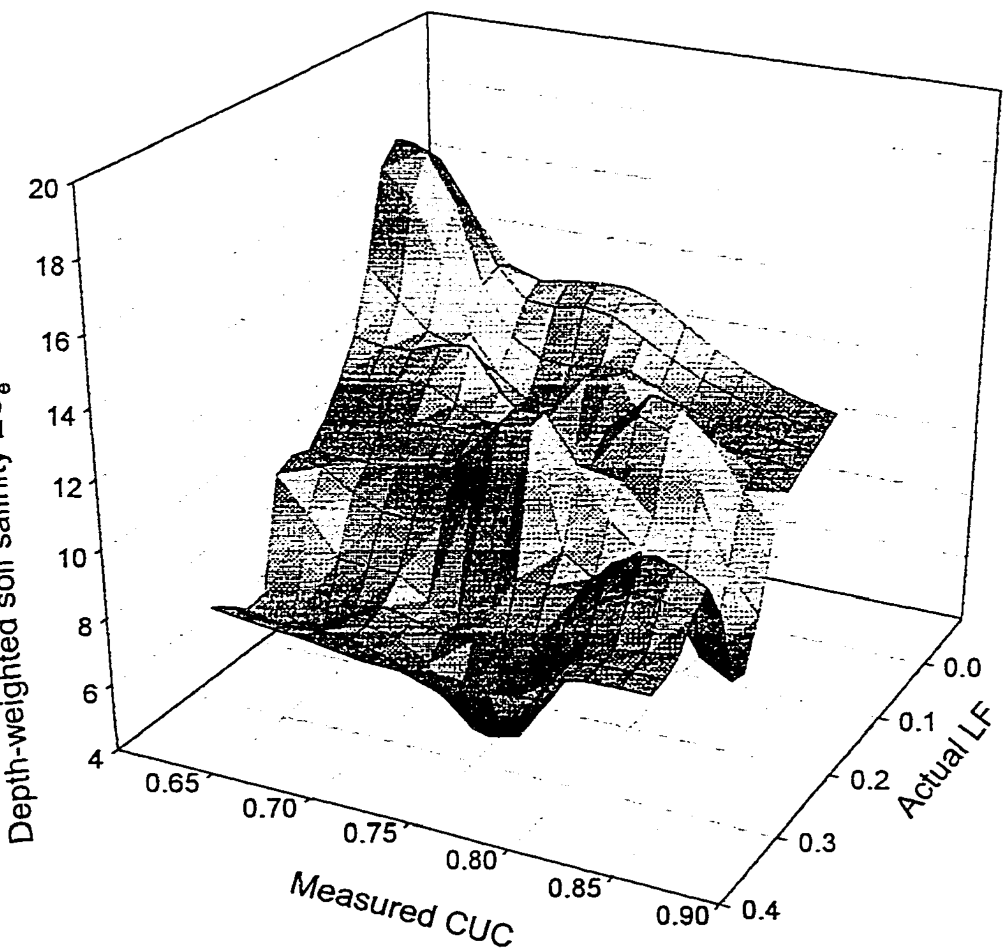

Fig. 3. Depth-weighted soil salinity as a function of the actual leaching fraction (LF) and the measured Christiansen Uniformity Coefficient (CUC) measured at the end of 18 months of treatment

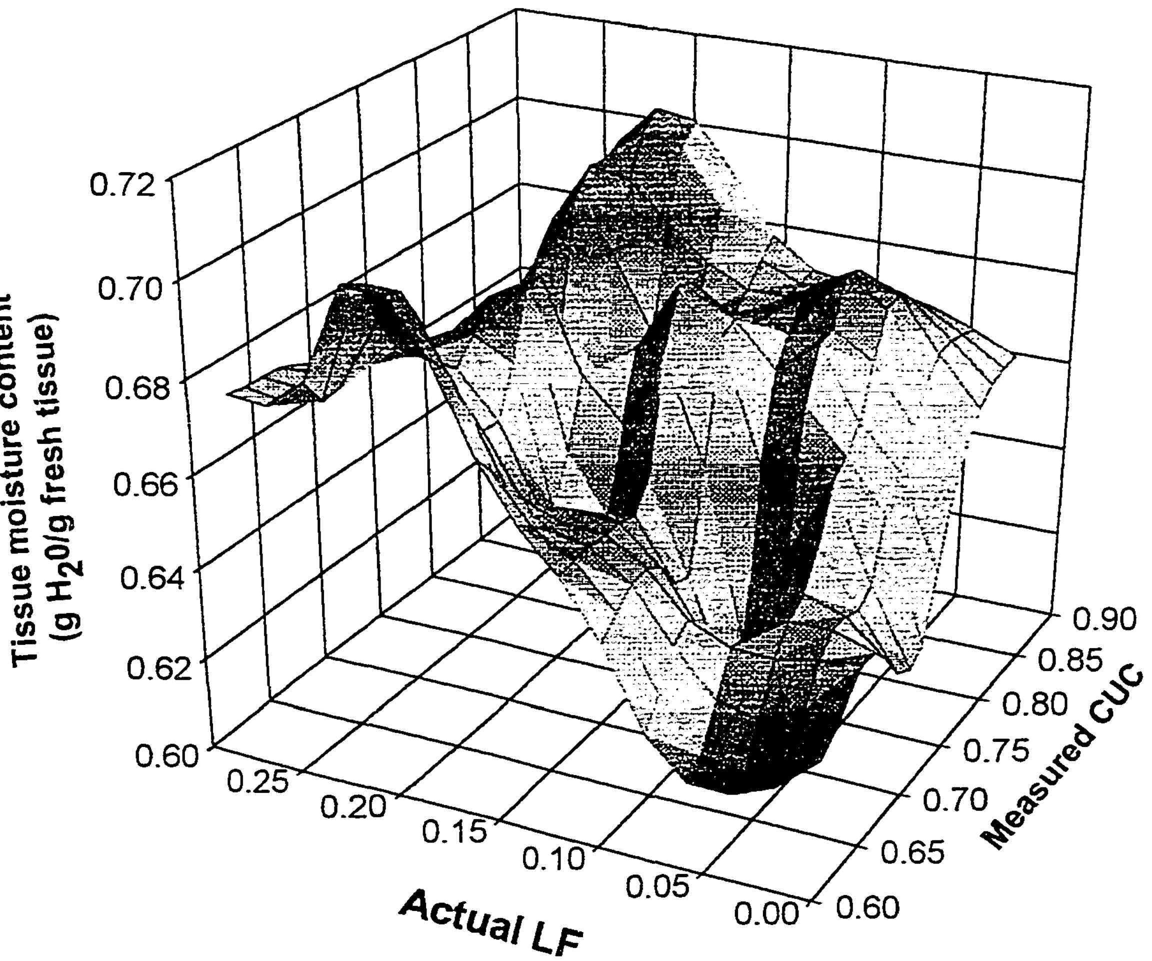

Fig. 4. Tissue moisture content [(g water) (g fresh tissue)$^{-1}$] as a function of the actual leaching fraction (LF) and the measured Christiansen Uniformity Coefficient (CUC) measured at the end of 18 months of treatment

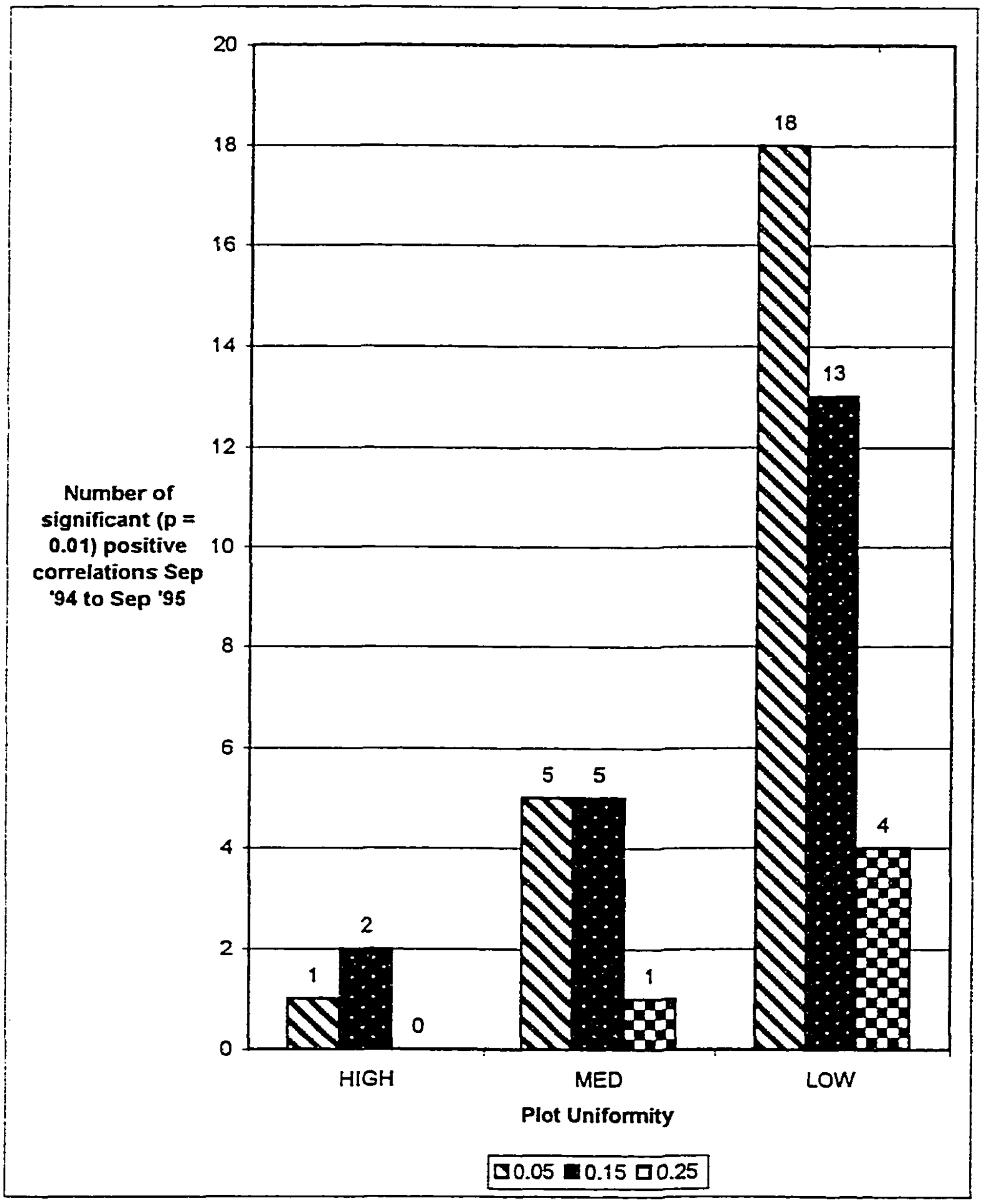

Fig. 5. Number of significant Spearman rank correlations between successive canopy temperature sampling events. Total number of measurements was 468 and the total number of positive correlations was 49 (correlation significant (**) when r > 0.52)

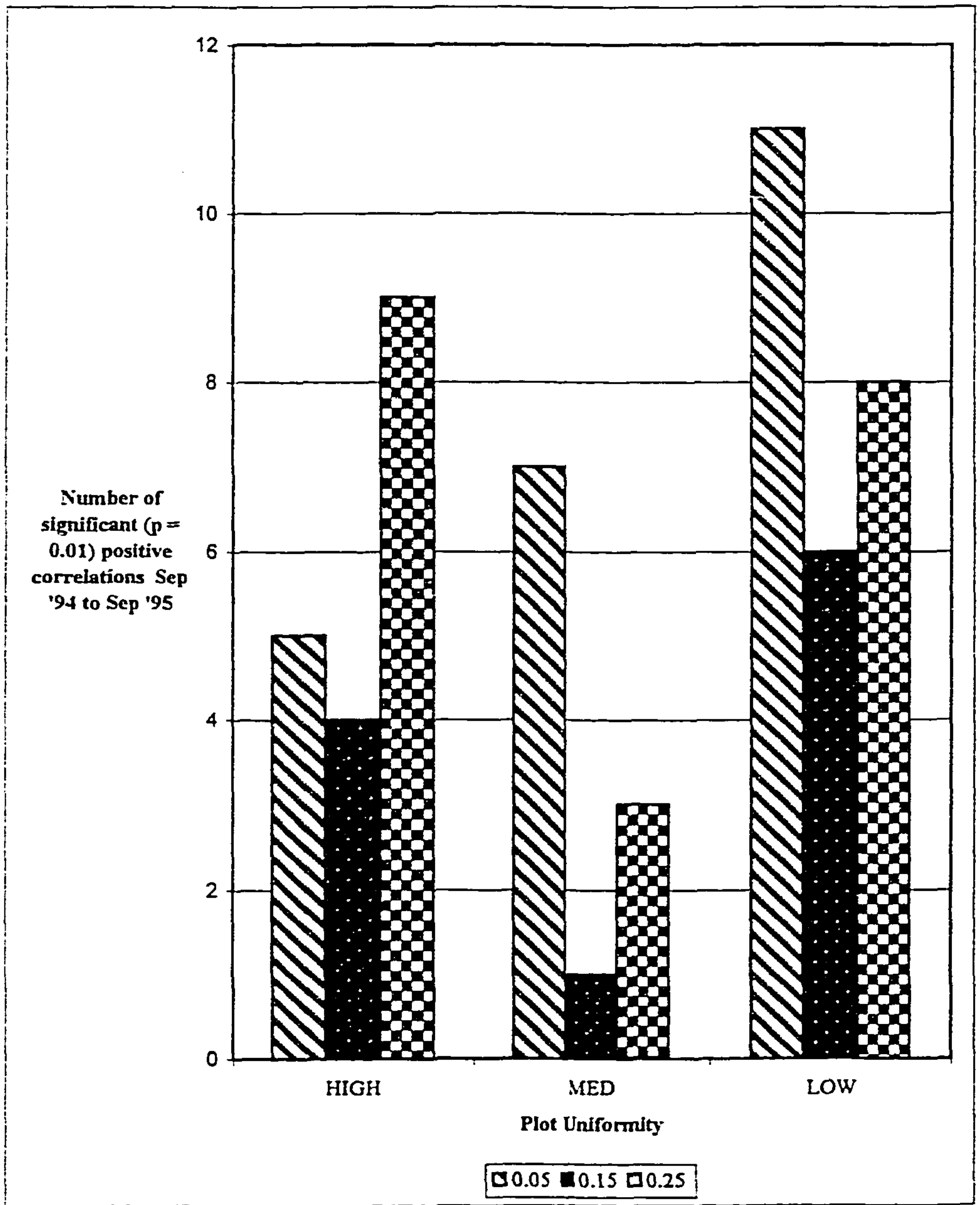

Fig. 6. Number of significant Spearman rank correlations between successive tissue moisture content sampling events. Total number of measurements was 234, and the total number of positive correlations was 54 (correlation significant (**) when r > 0.52)

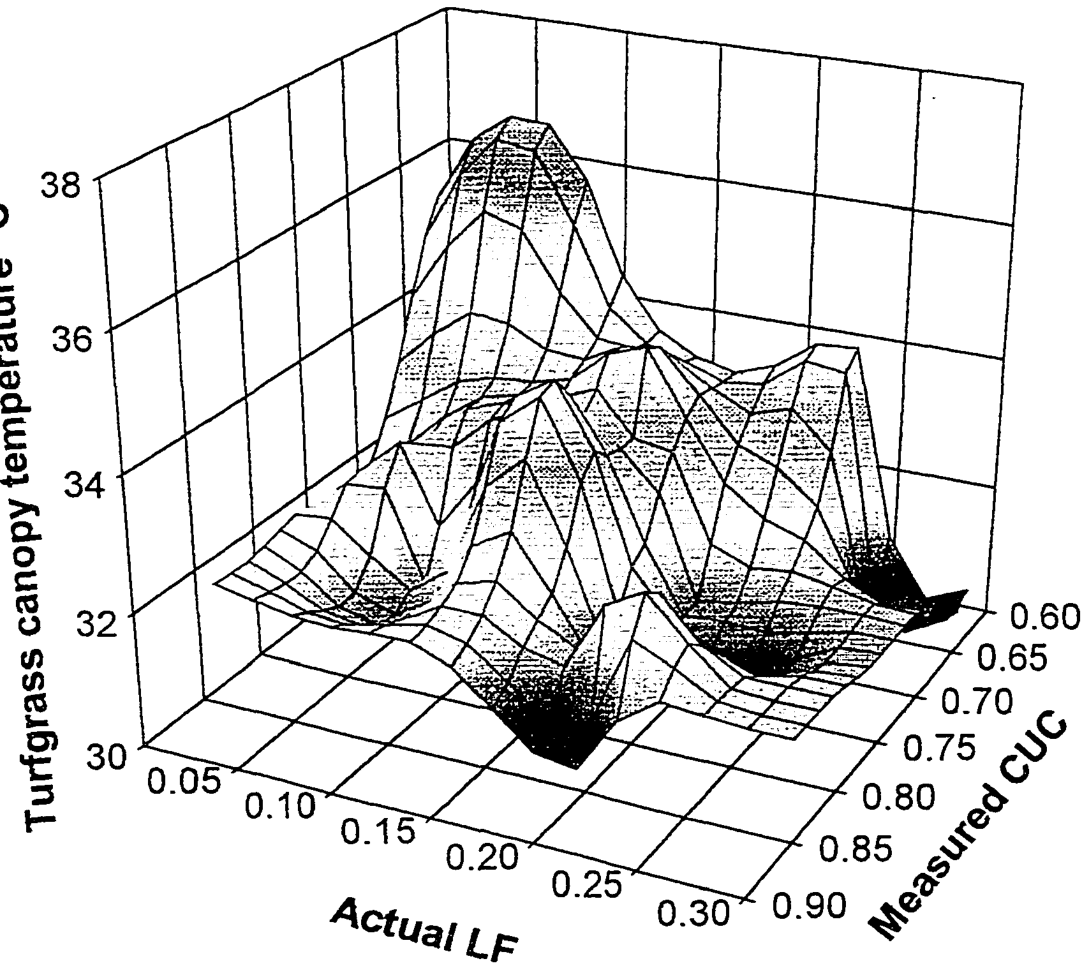

Fig. 7. Turfgrass canopy temperature (°C) as a function of the actual leaching fraction (LF) and the measured Christiansen Uniformity Coefficient (CUC) measured at the end of 18 months of treatment

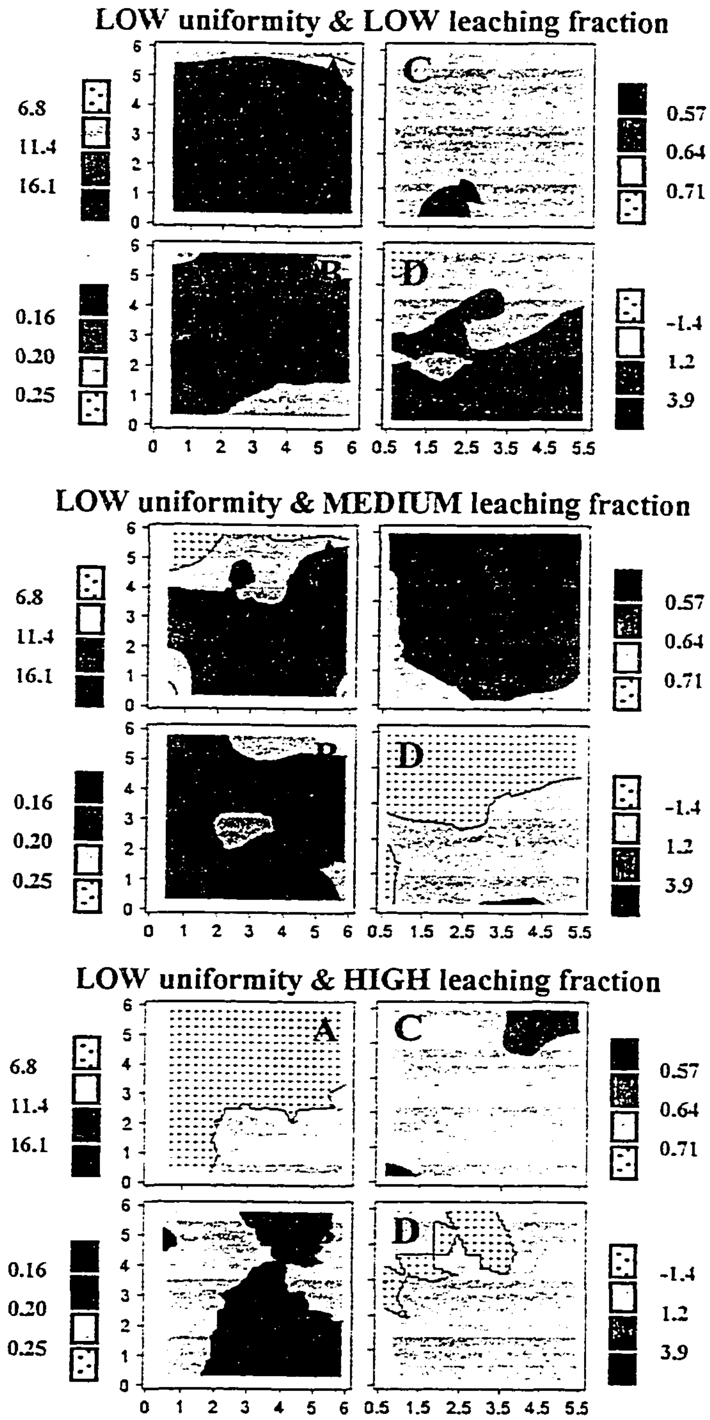

Fig. 8. Contour maps of soil salinity (map A: EC_e, 0 to 15 cm), θ_g (map B: 0 to 15 cm), tissue moisture content (map C), and $T_c - T_a$ (map D). Maps include low uniformity plots with increasing LF, measured at the end of 18 months of treatment

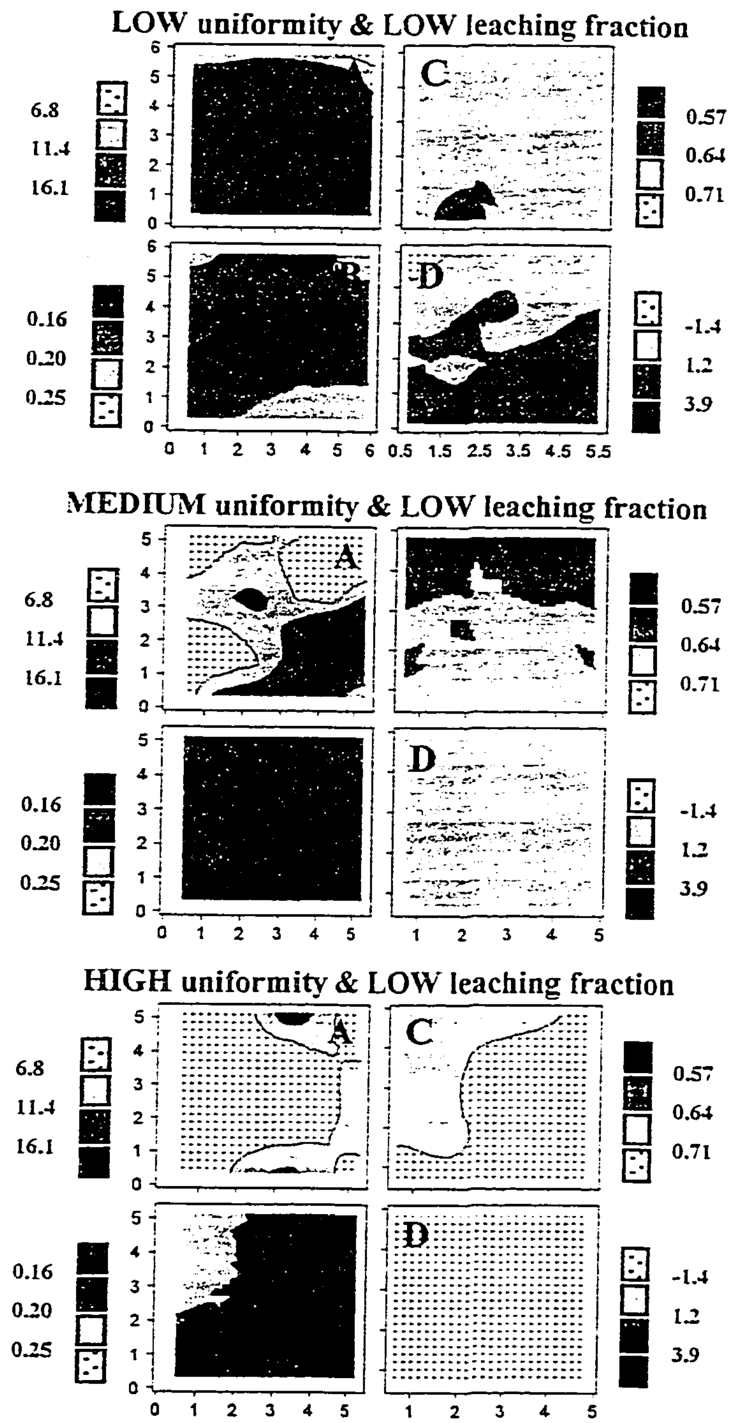

Fig. 9. Contour maps of soil salinity (map A: EC_e, 0 to 15 cm), θ_g (map B: 0 to 15 cm), tissue moisture content (map C), $T_c - T_a$ (map D). Maps include low LF plots with increasing uniformity, measured at the end of 18 months of treatment

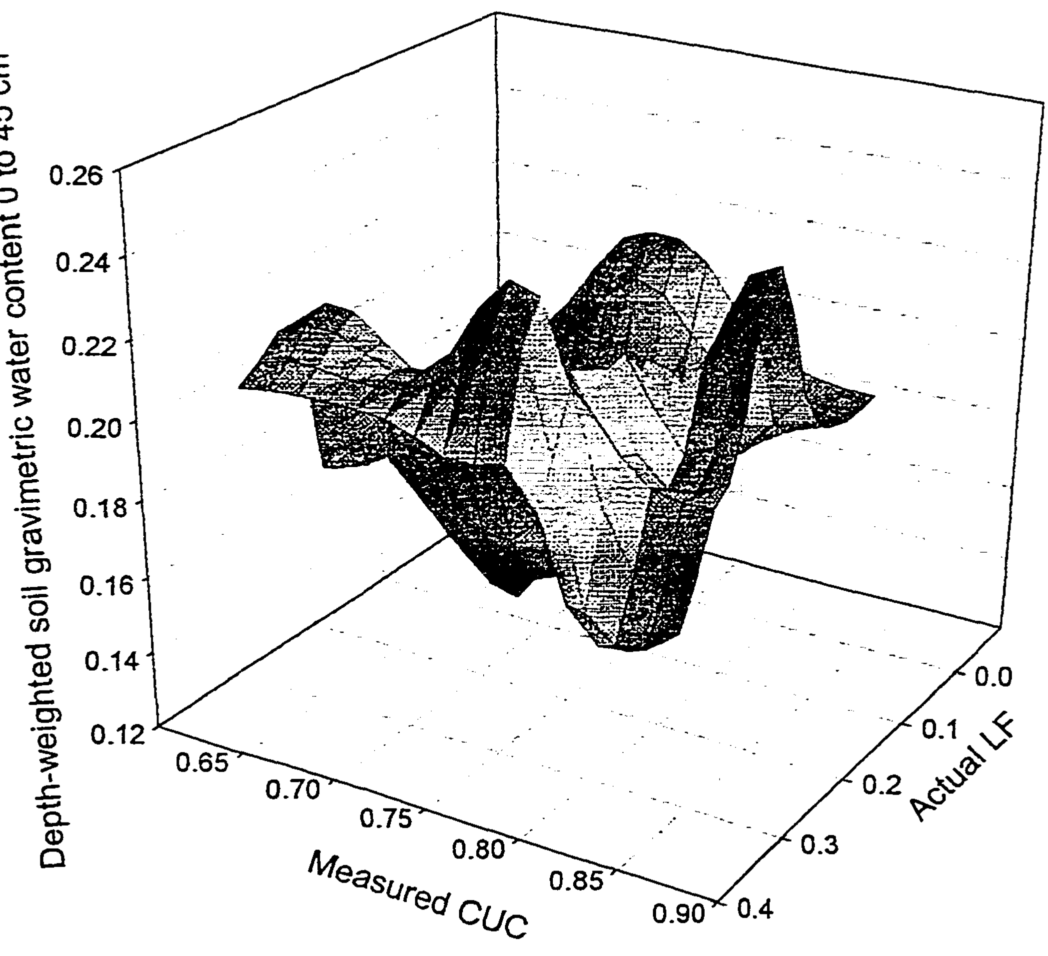

Fig. 10. Depth-weighted soil gravimetric water content as a function of the leaching fraction (LF) and the Christiansen Uniformity Coefficient (CUC) measured at the end of 18 months of treatment (compare to Fig.s 3 and 18)

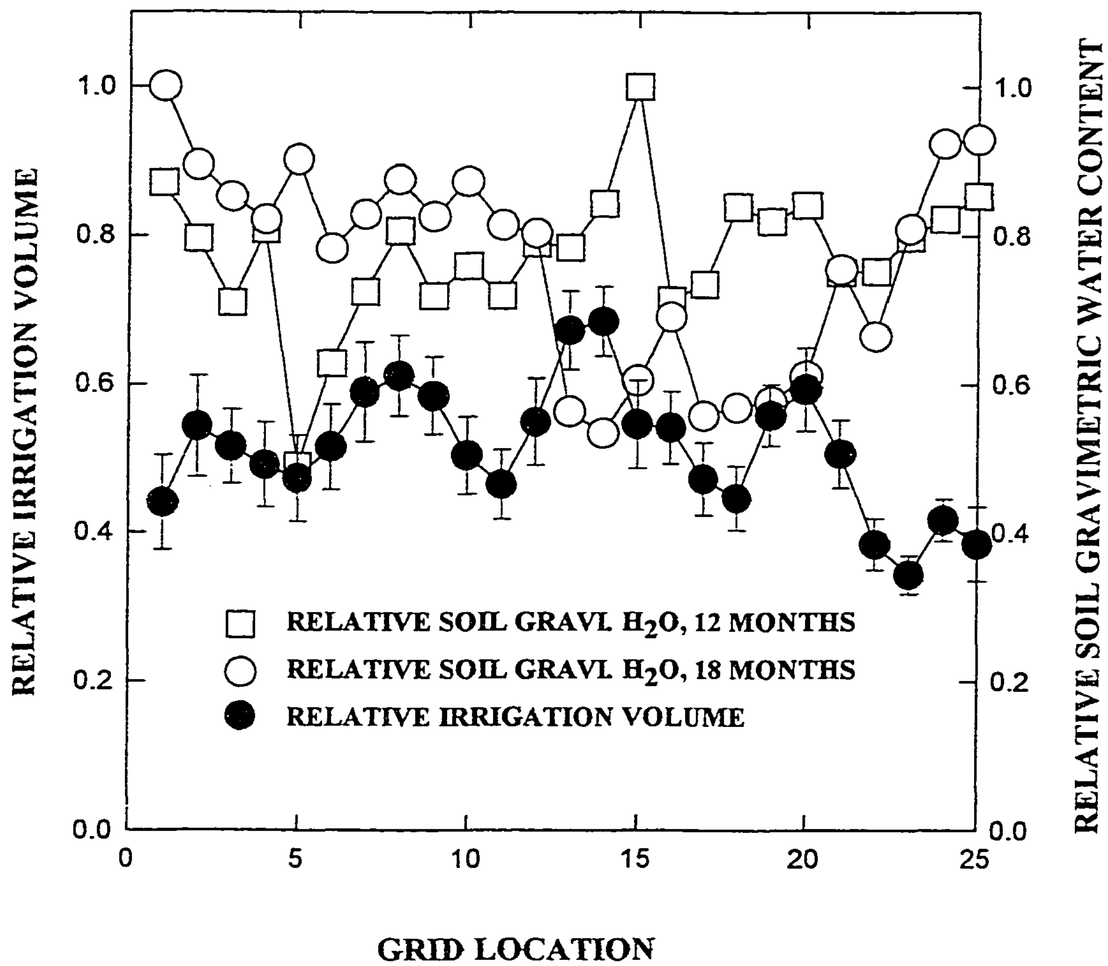

Fig. 11. Relative irrigation volume (average of 22 sampling dates) and soil gravimetric water contents measured at 25 grid locations (location 1 represents NW corner, location 25 represents SE corner of plot situated in a 5 x 5 grid pattern) within a 0.05 LF, 0.65 CUC plot. Relative values are irrigation volumes or gravimetric water contents measured at each grid location divided by the maximum value measured in the 25 grid locations

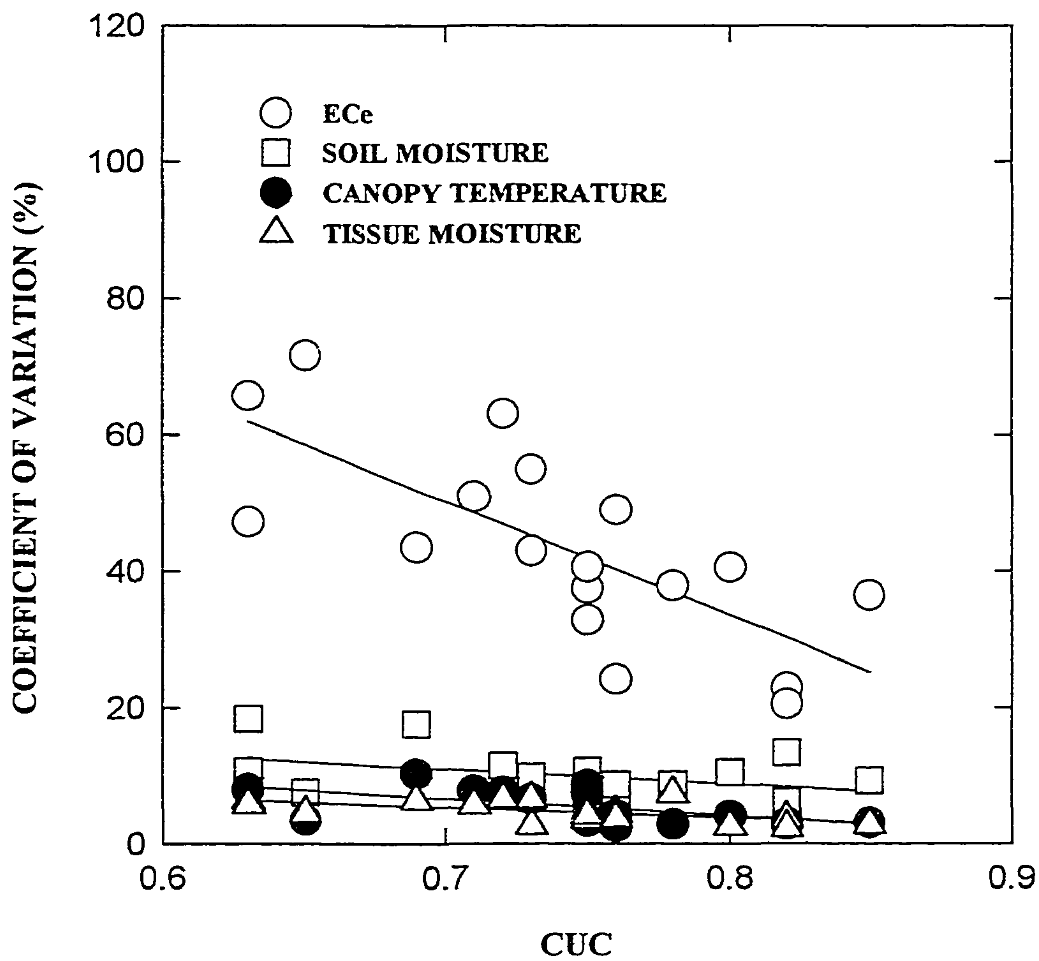

Fig. 12. Coefficient of variation for EC_e($r = 0.73$ ***, slope = - 167.0), actual canopy temperature ($r = 0.62$ ***, slope = - 25.0), soil gravimetric water content ($r = 0.39$, slope = - 22.0), and tissue moisture content ($r = 0.58$ **, slope = - 15.0)as a function of actual CUC for all 18 plots.

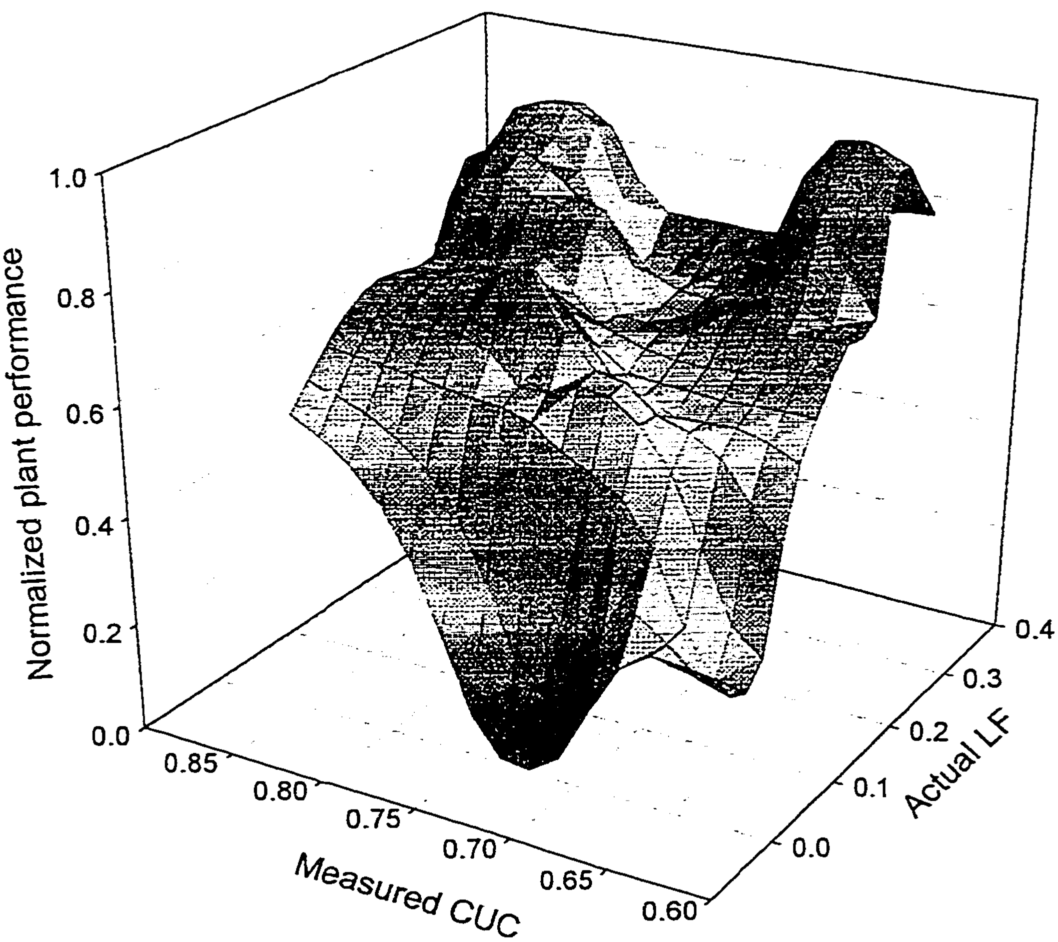

Fig. 13. Normalized plant performance as a function of the leaching fraction (LF) and the Christiansen Uniformity Coefficient (CUC)

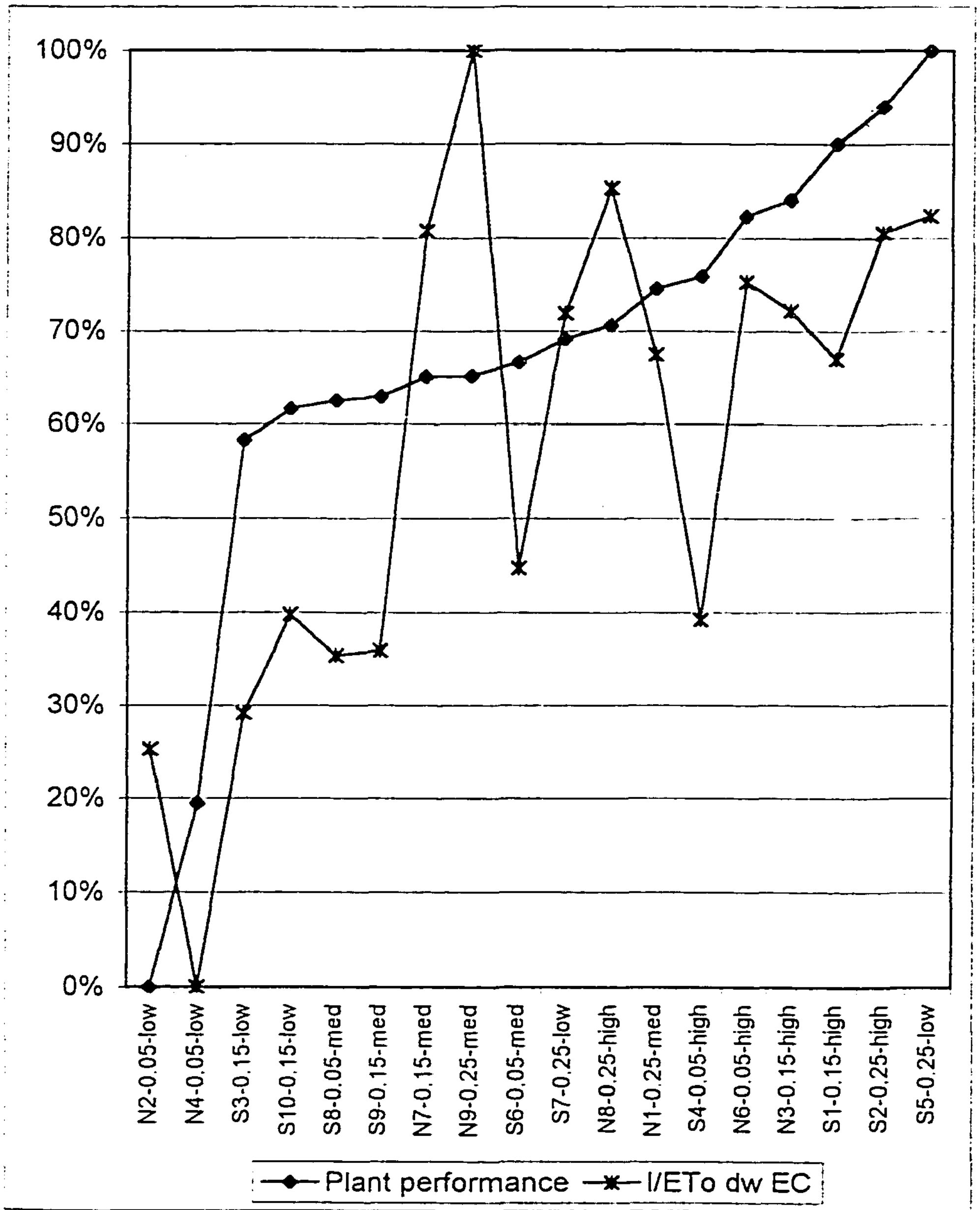

Fig. 14. Treatments vs. normalized plant performance (normalized sum of equally weighted averaged delta canopy temperatures ($T_c - T_a$) and of tissue moisture contents) and vs. normalized sum of I/ET_o and depth-weighted salinity 0 to 45 cm (dS m^{-1}), each equally weighted, n = 18

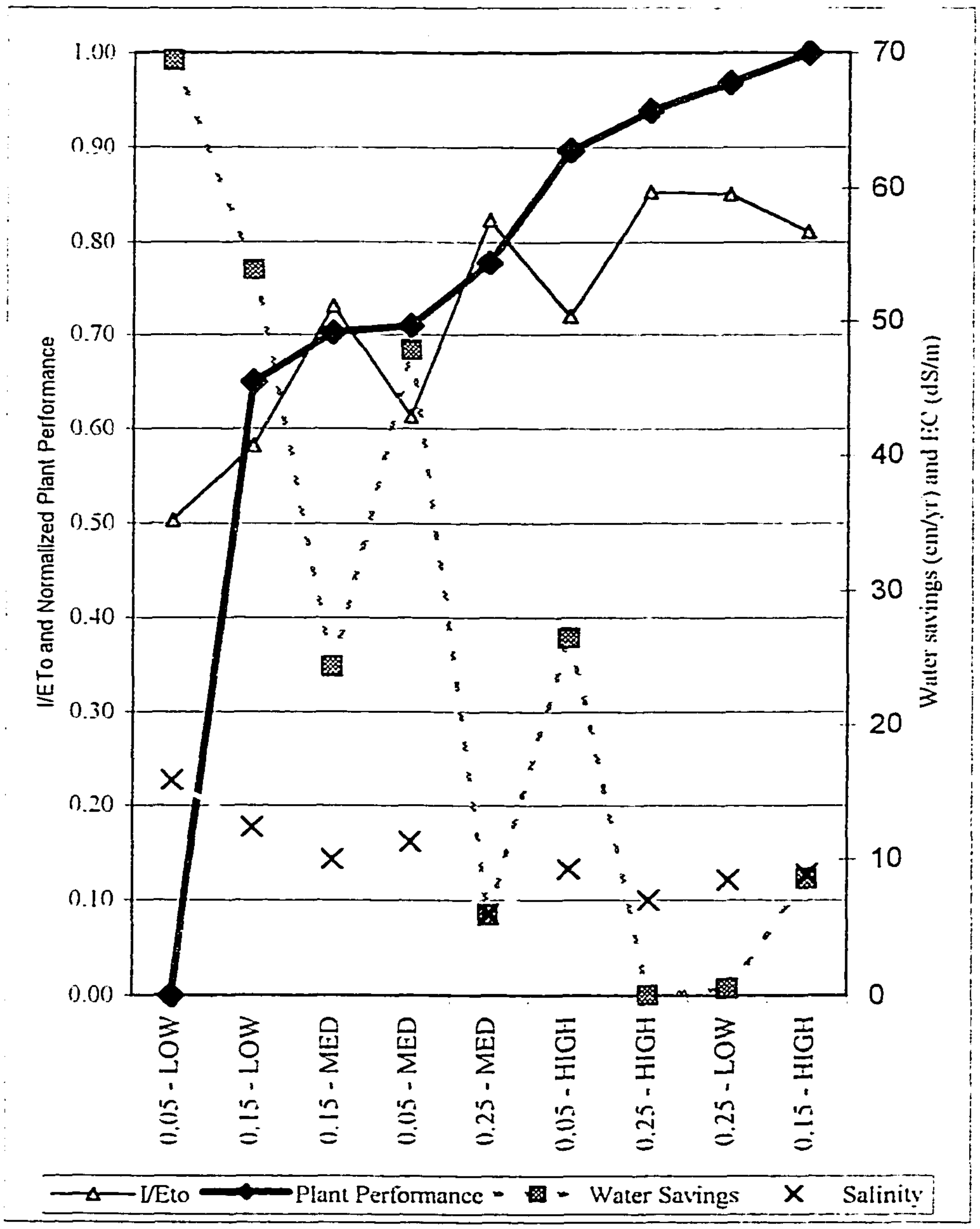

Fig. 15. Averaged treatment normalized plant performances (i.e. the normalized sum of equally weighted averaged delta canopy temperatures ($T_c - T_a$) and tissue moisture contents), and depth-weighted soil salinity 0 to 45 cm (dS m^{-1}), water savings (cm m^2 yr^{-1}) and I/ET_o [cm water (cm water)$^{-1}$], n = 9

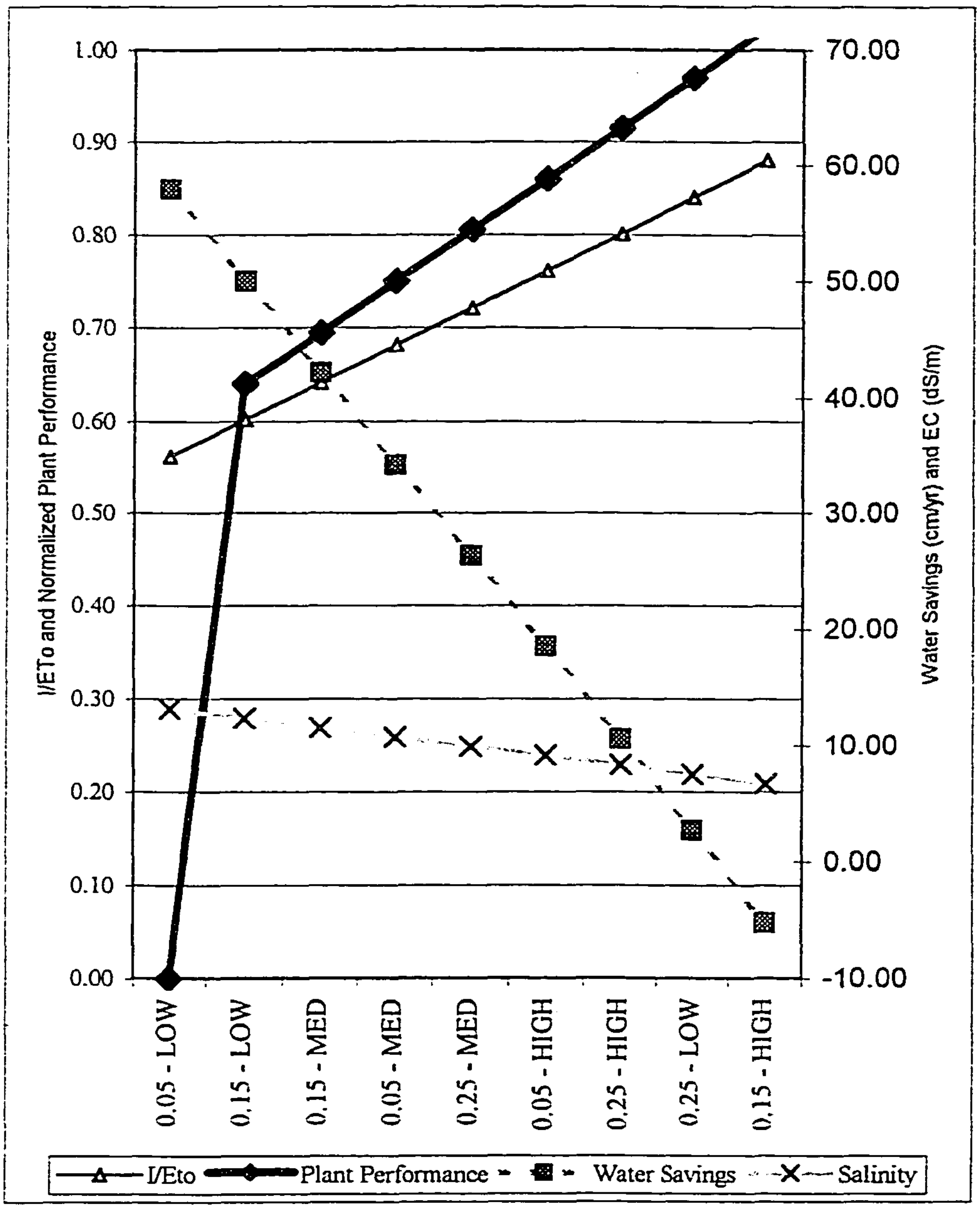

Fig. 16. Averaged treatments vs. linearly regressed normalized plant performances (i.e. the normalized sum of equally weighted averaged delta canopy temperatures ($T_c - T_a$) and tissue moisture contents), vs. linearly regressed depth-weighted soil salinity 0 to 45 cm (dS m^{-1}), vs. linearly regressed water savings (cm-m^2 yr^{-1}) and vs. linearly regressed I/ET_o ratio [cm water (cm water)$^{-1}$], n = 9

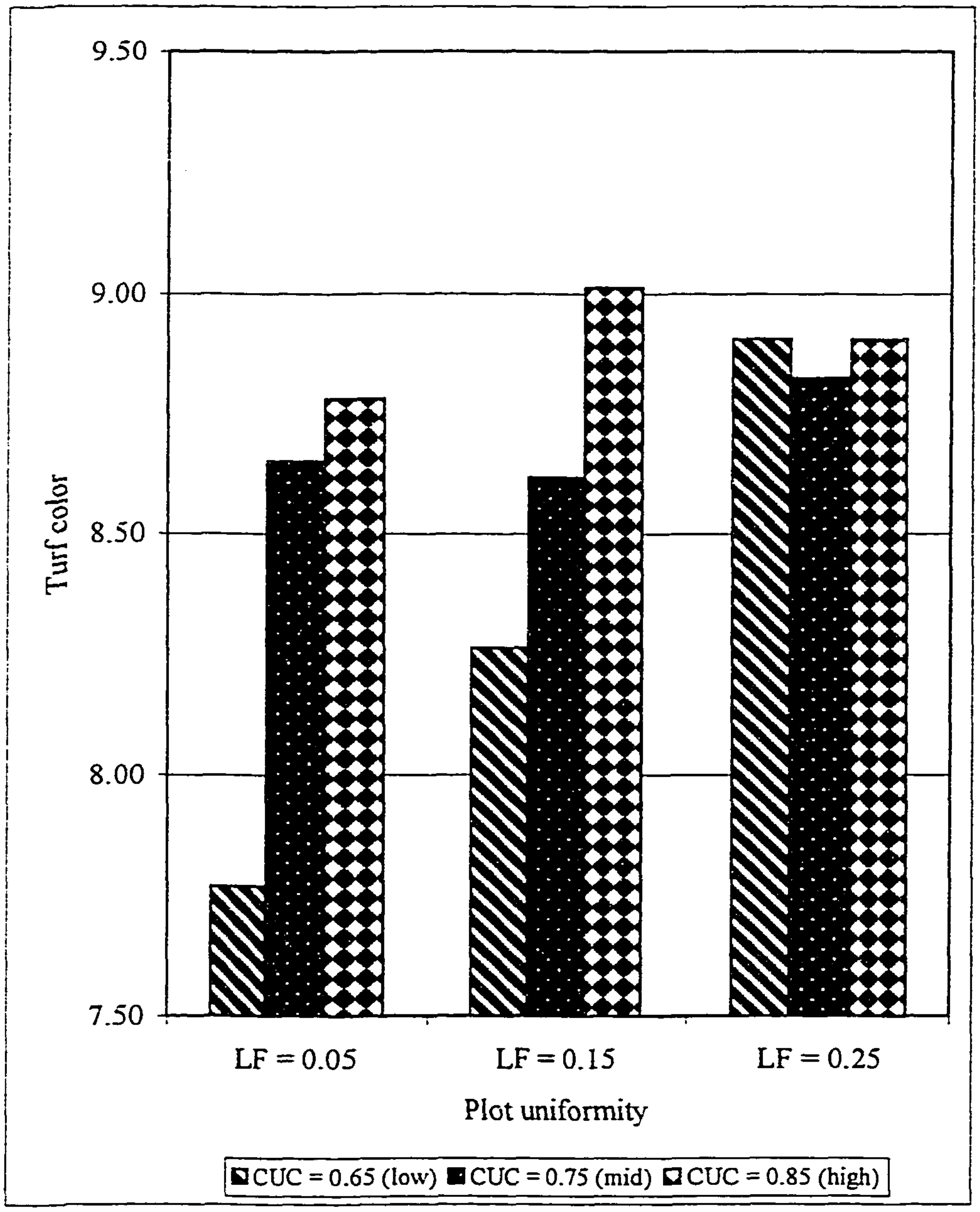

Fig. 17. Turf color vs. imposed LF x CUC treatments. Correlation developed by Brown et al. (1997), where turf color = 9.36 (tissue moisture content) + 2.90

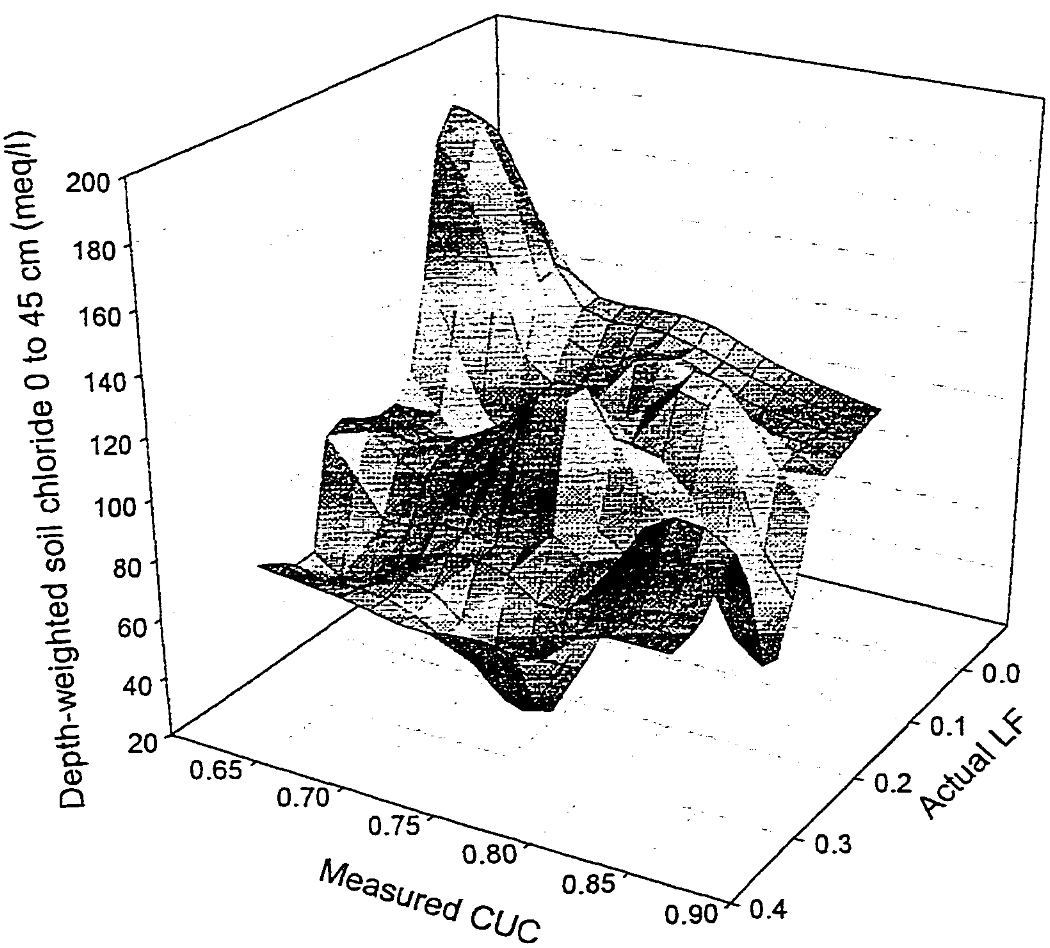

Fig. 18. Depth-weighted soil chloride as a function of the leaching fraction (LF) and the Christiansen Uniformity Coefficient (CUC) measured at the end of 18 months of treatment (compare to Figures 3 and 10)

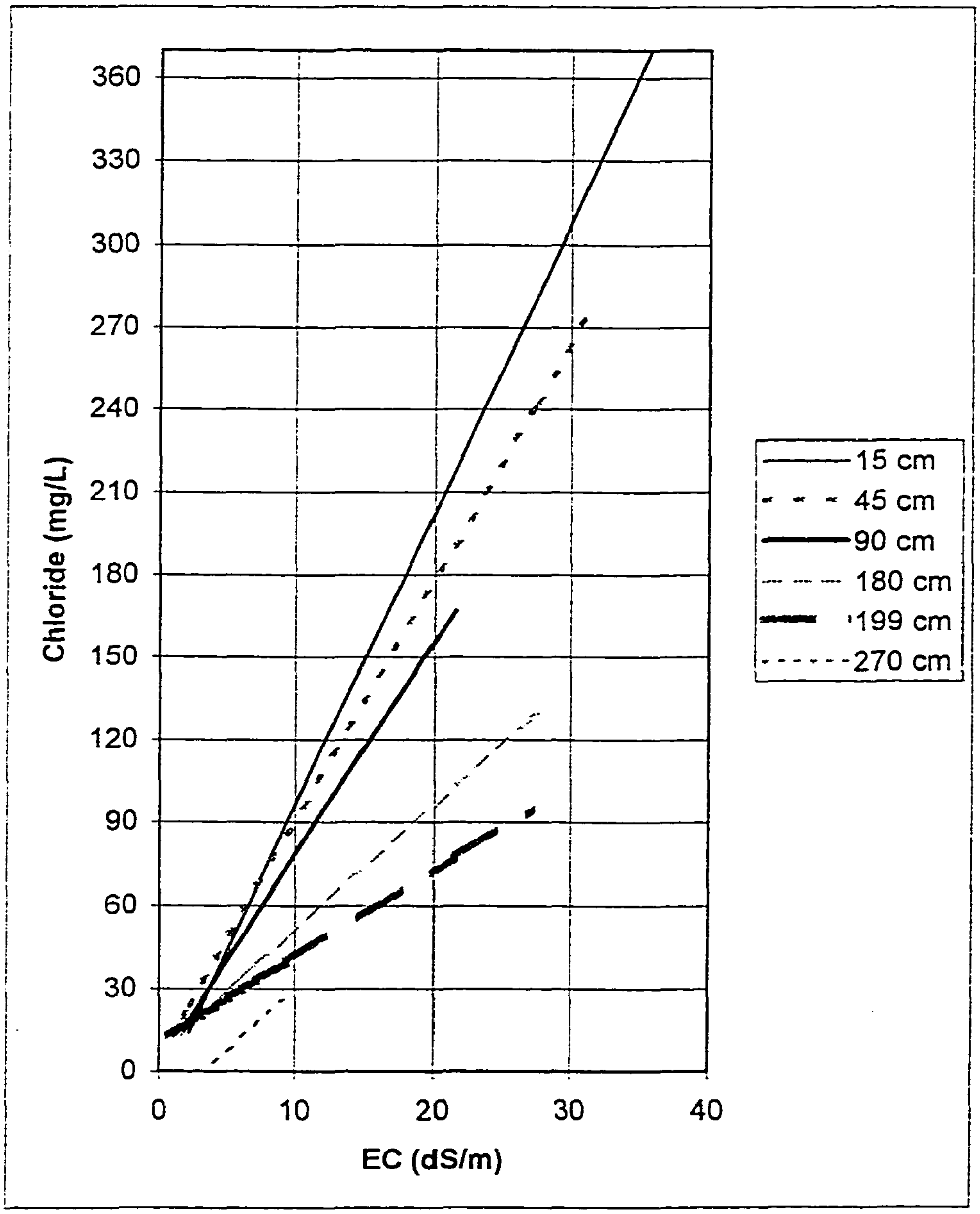

Fig. 19. Soil chloride/EC_e ratio at various soil depths. All data has been linearly regressed The length of the lines reflect the range of values. At 0 to 15 cm, $r^2 = 0.85$ ***, n = 576, slope = 10.6. At 15 to 45 cm, $r^2 = 0.64$ ***, n = 538, slope = 8.6. At 75 to 90 cm, $r^2 = 0.68$ ***, n = 179, slope = 7.7. At 165 to 180 cm, $r^2 = 0.59$ ***, n = 176, slope = 4.5. At ~ 185 to 200 cm, $r^2 = 0.33$ ***, n = 147, slope = 3.1. At 255 to 275 cm, $r^2 = 0.45$ ***, n = 36, slope = 4.7.

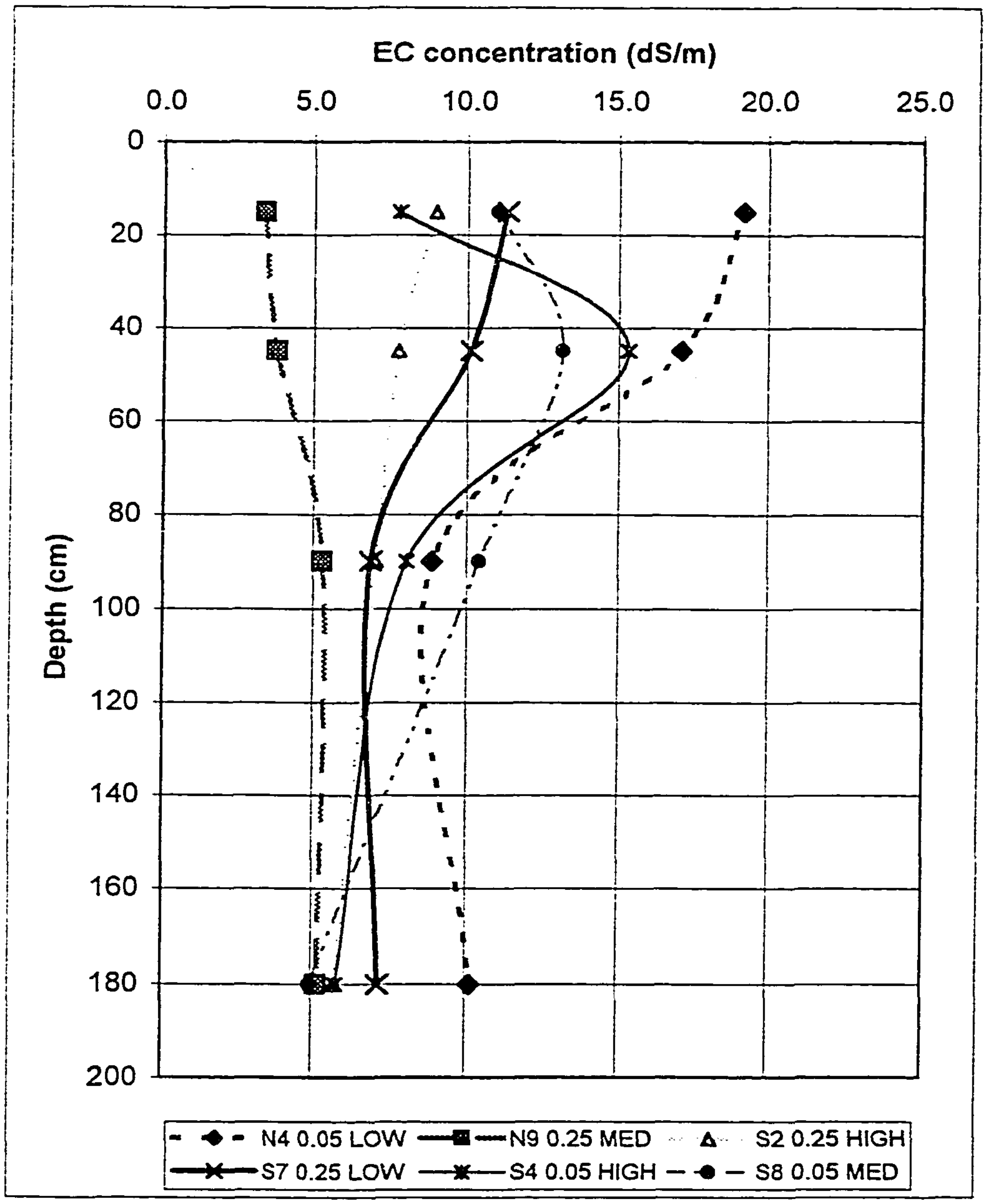

Fig. 20. EC_e concentration (dS m^{-1}) vs. depth

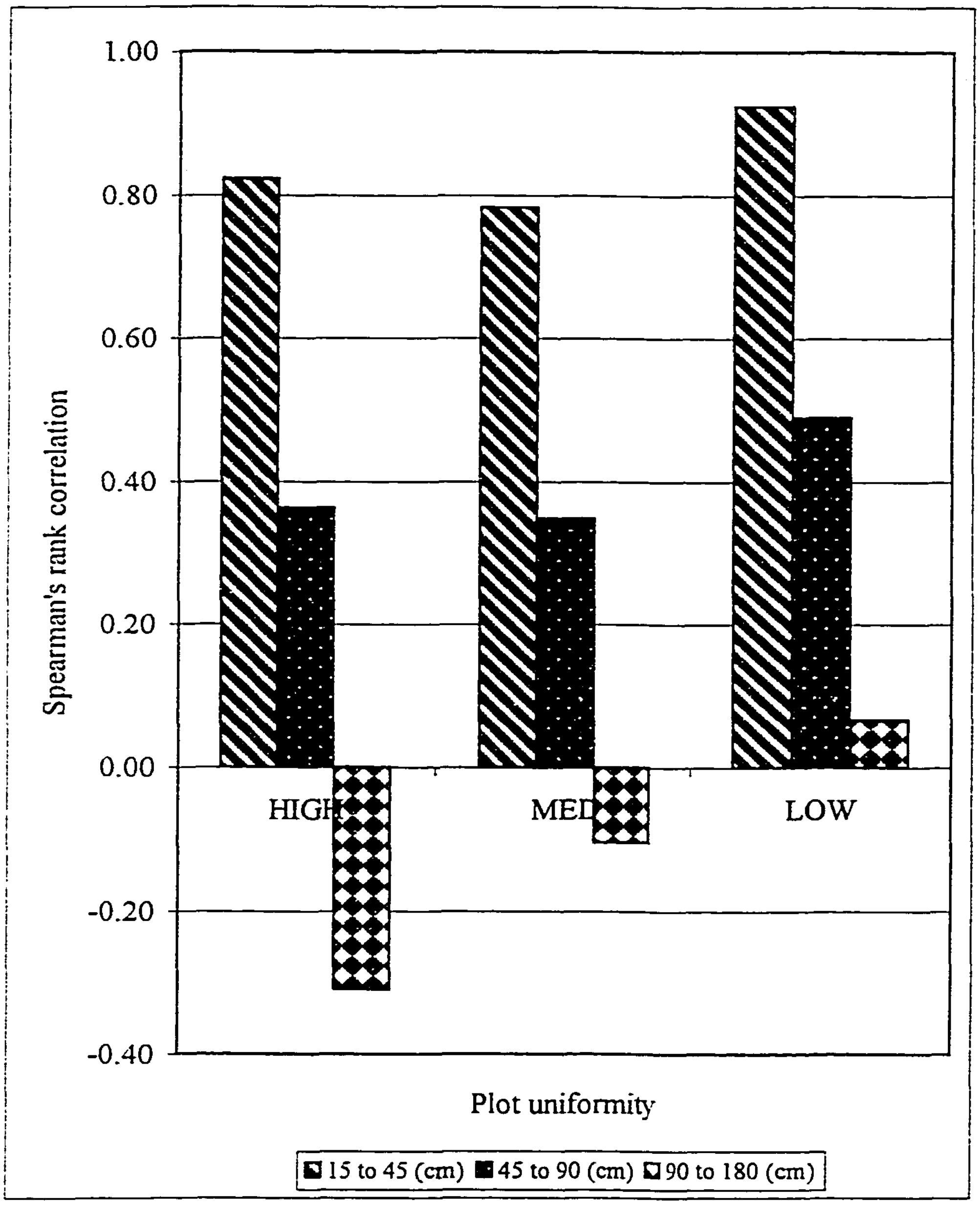

Fig. 21. Soil chloride Spearman rank correlations for LF = 0.05 with the overlying sampling interval (i.e. 0 to 15 cm with 15 to 45 cm, 15 to 45 cm with 75 to 90 cm, and 75 to 90 cm with 165 to 180 cm) for the deep-sampled plots

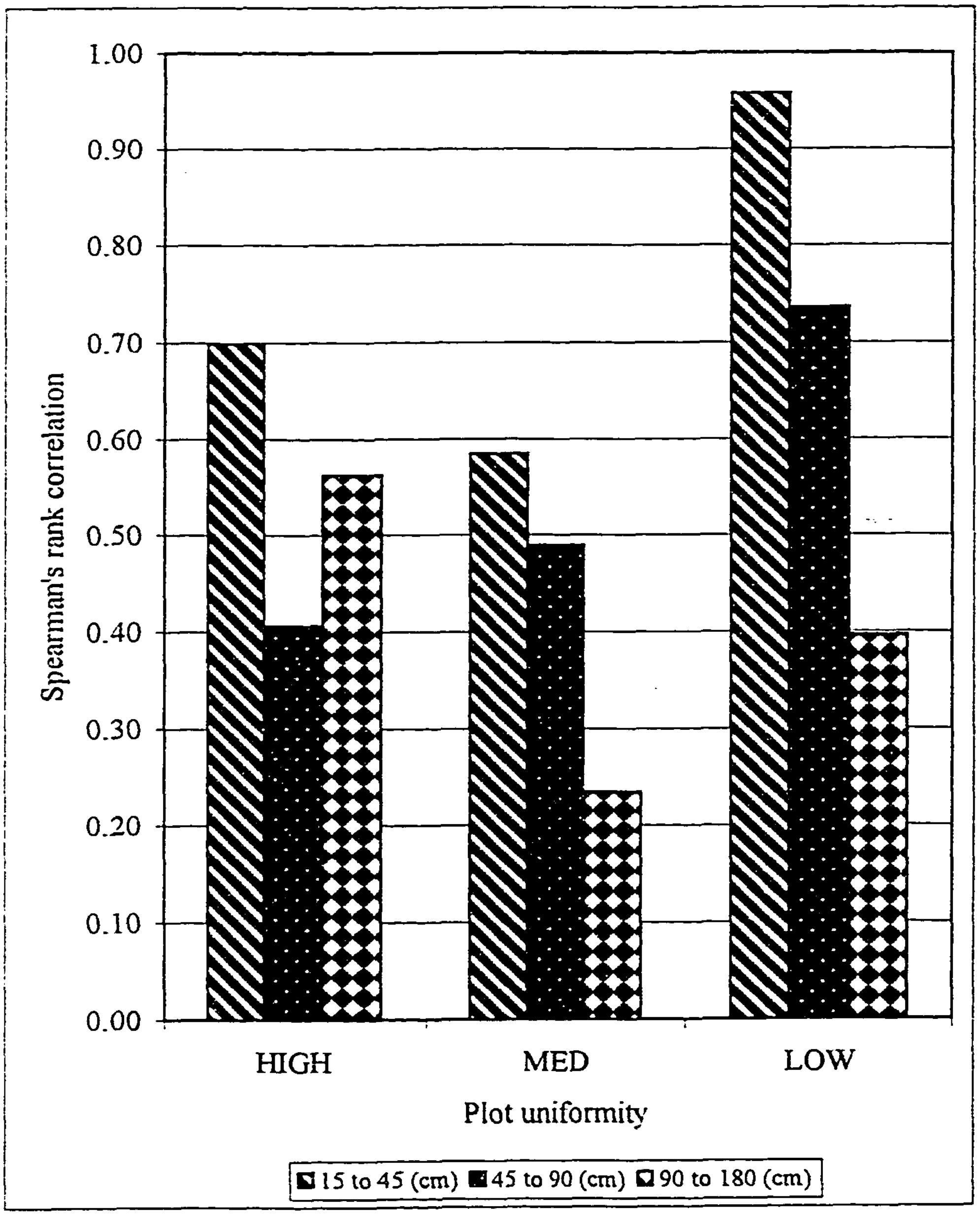

Fig. 22. Soil chloride Spearman rank correlations for LF = 0.25 with the overlying sampling interval (i.e. 0 to 15 cm with 15 to 45 cm, 15 to 45 cm with 75 to 90 cm, and 75 to 90 cm with 165 to 180 cm) for the deep-sampled plots

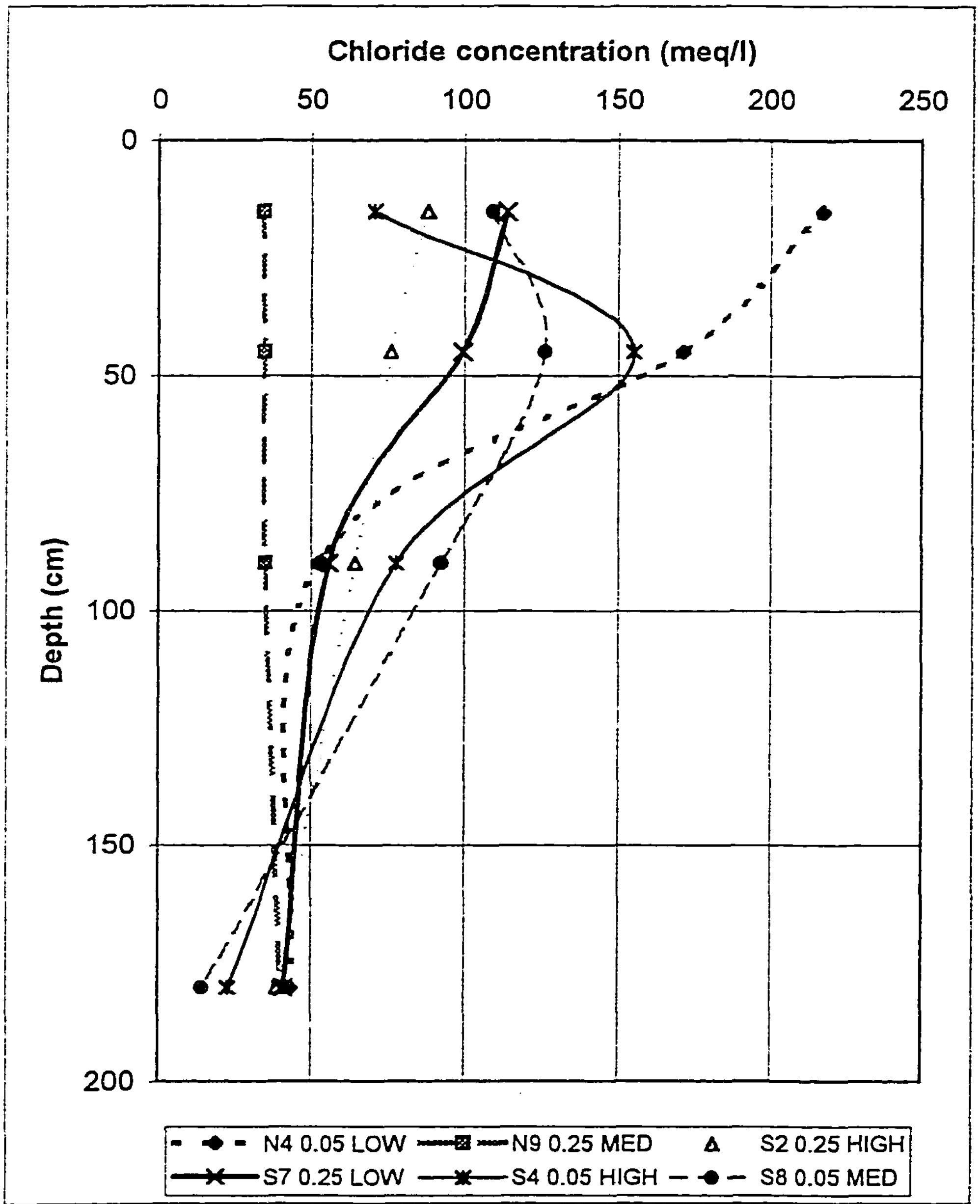

Fig. 23. Chloride concentration (meq l^{-1}) vs. depth

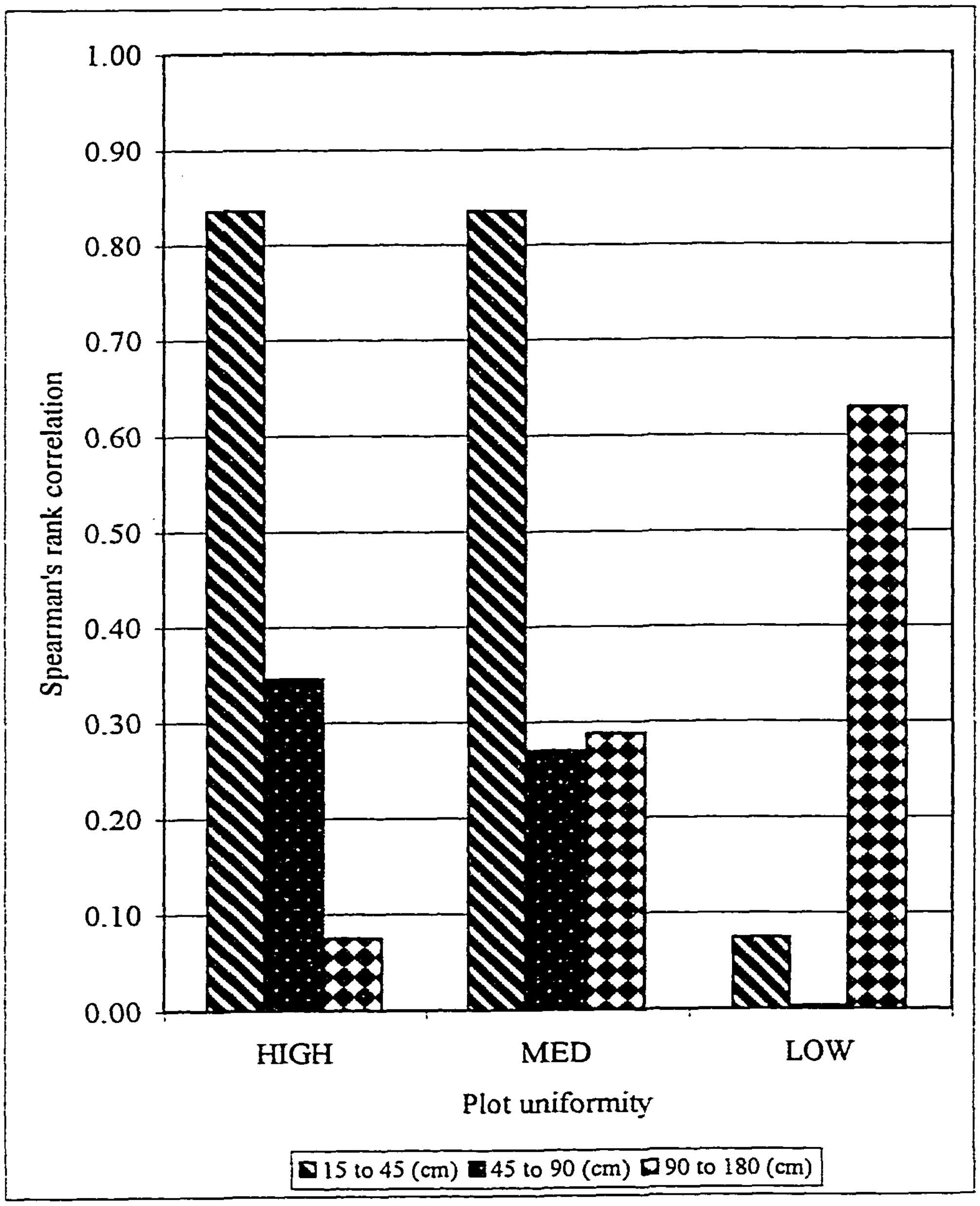

Fig. 24. Soil EC Spearman rank correlations for LF = 0.05 with the overlying sampling interval (i.e. 0 to 15 cm with 15 to 45 cm, 15 to 45 cm with 75 to 90 cm, and 75 to 90 cm with 165 to 180 cm) for the deep-sampled plots

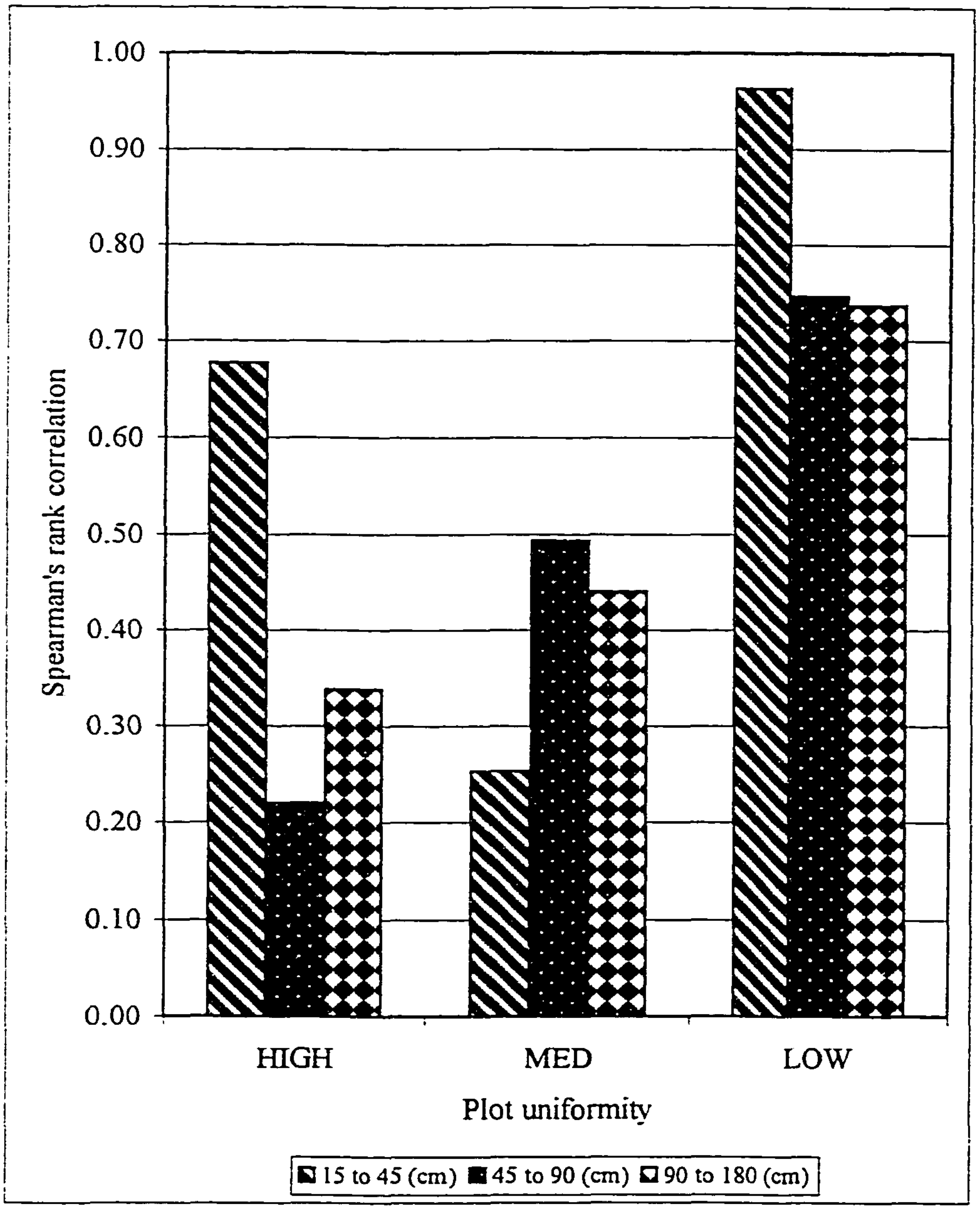

Fig. 25. Soil EC Spearman rank correlations for LF = 0.25 with the overlying sampling interval (i.e. 0 to 15 cm with 15 to 45 cm, 15 to 45 cm with 75 to 90 cm, and 75 to 90 cm with 165 to 180 cm) for the deep-sampled plots

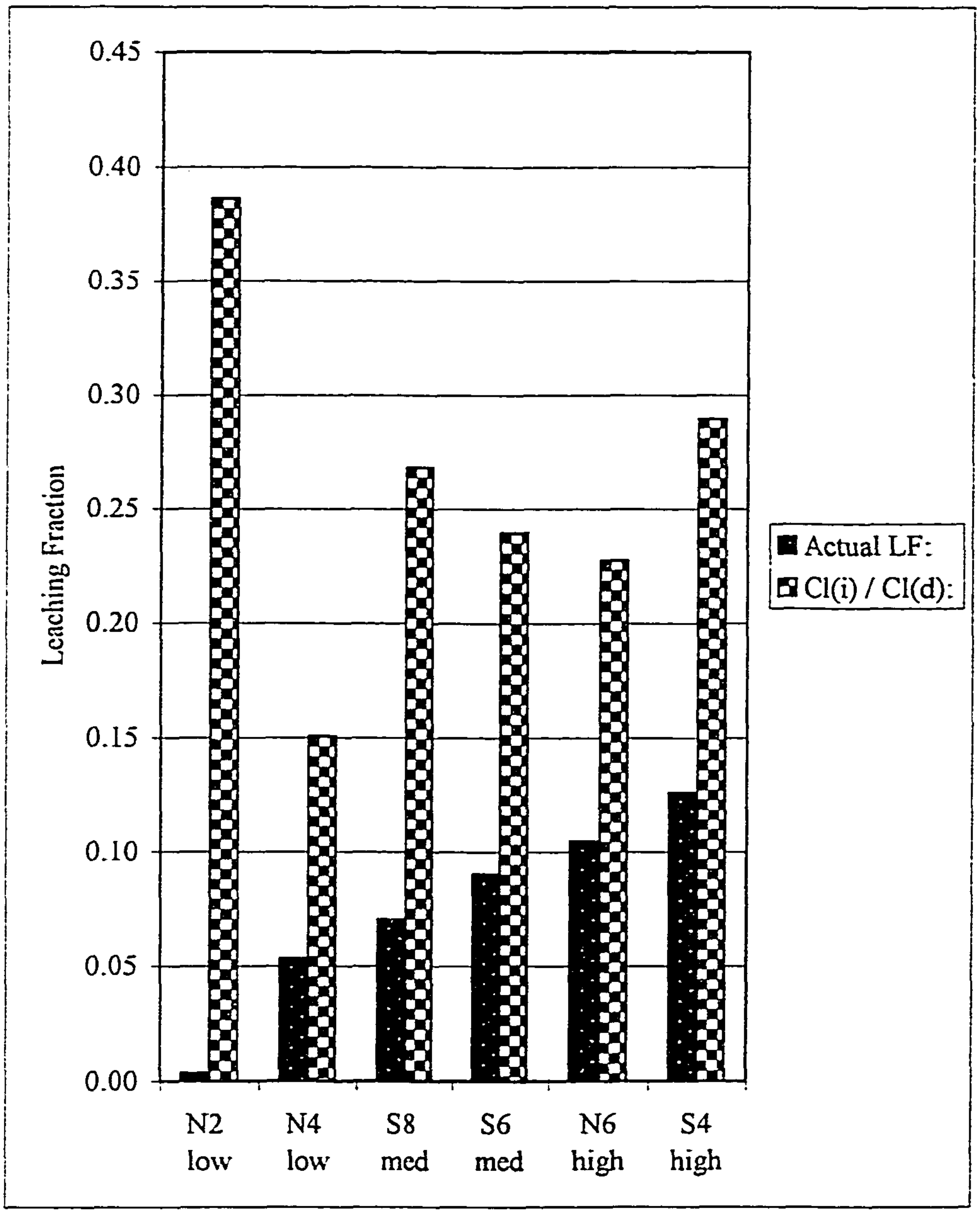

Fig. 26. For imposed LF = 0.05, predicted LFs based on chloride concentrations and irrigation volumes of drainage and irrigation (25 meq l^{-1} chloride)

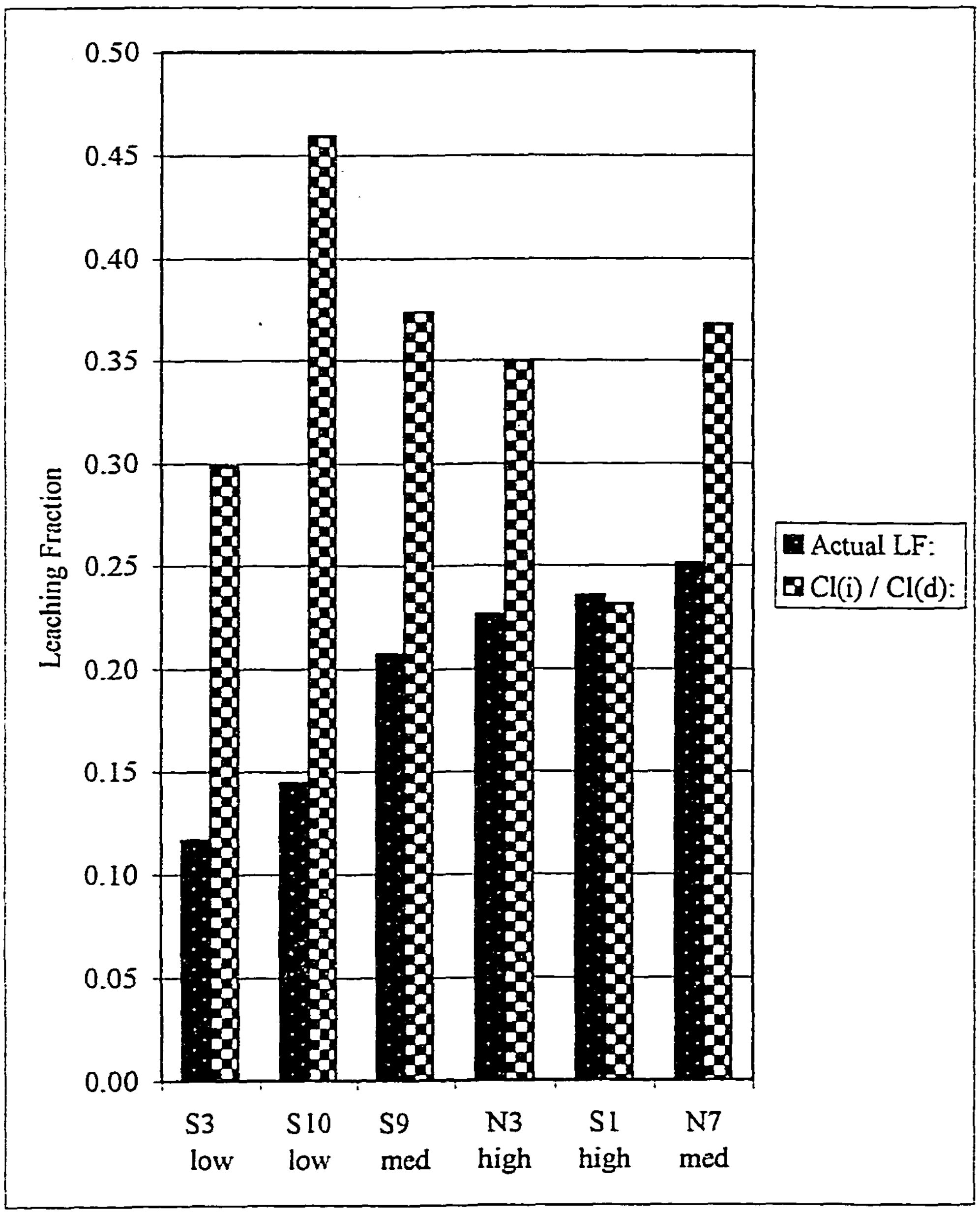

Fig. 27. For imposed LF = 0.15, predicted LFs based on chloride concentrations and irrigation volumes of drainage and irrigation (25 meq l^{-1} chloride)

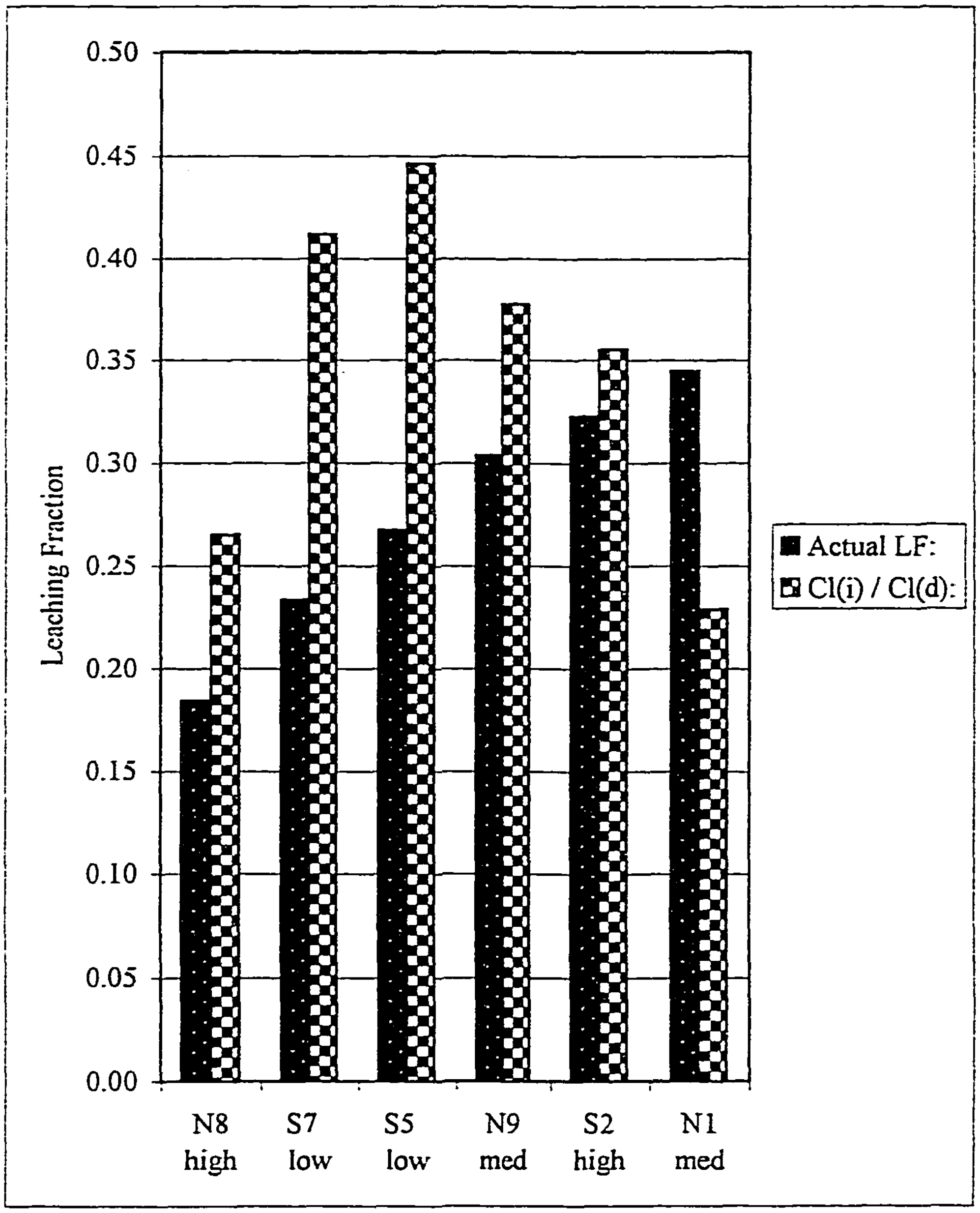

Fig. 28. For imposed LF = 0.25, predicted LFs based on chloride concentrations and irrigation volumes of drainage and irrigation (25 meq l^{-1} chloride)

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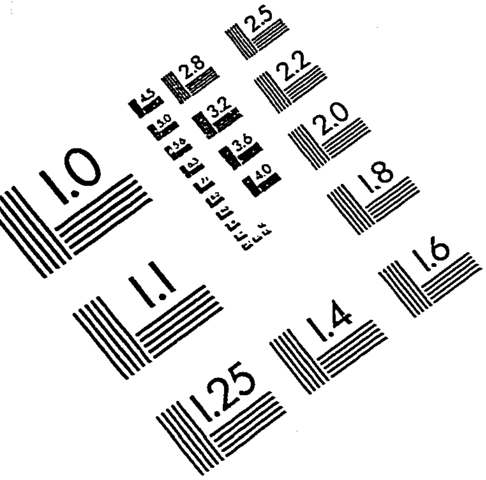
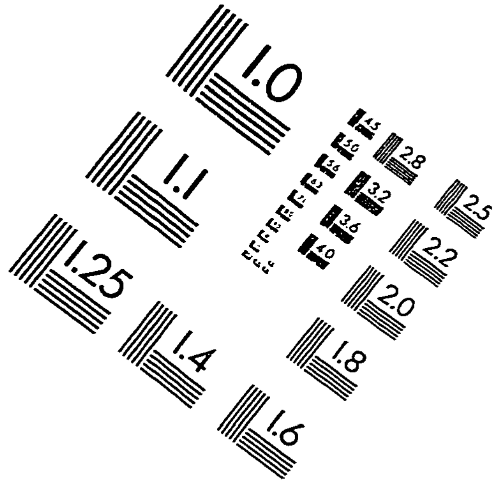
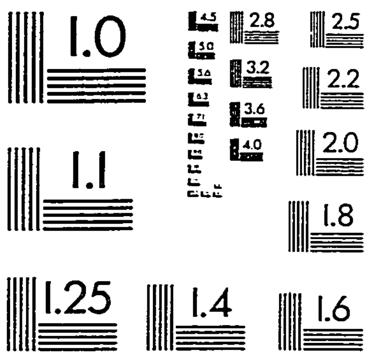
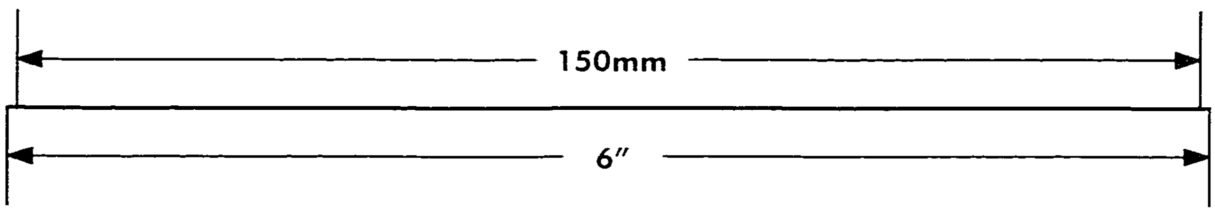
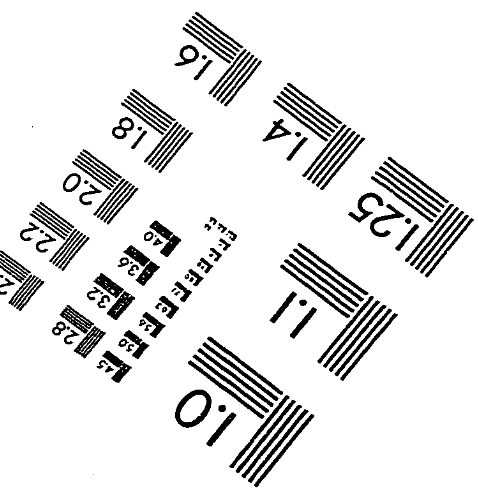
IMAGE EVALUATION TEST TARGET (QA-3)

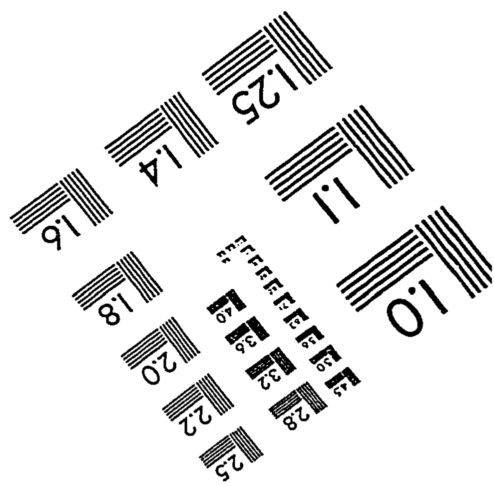












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