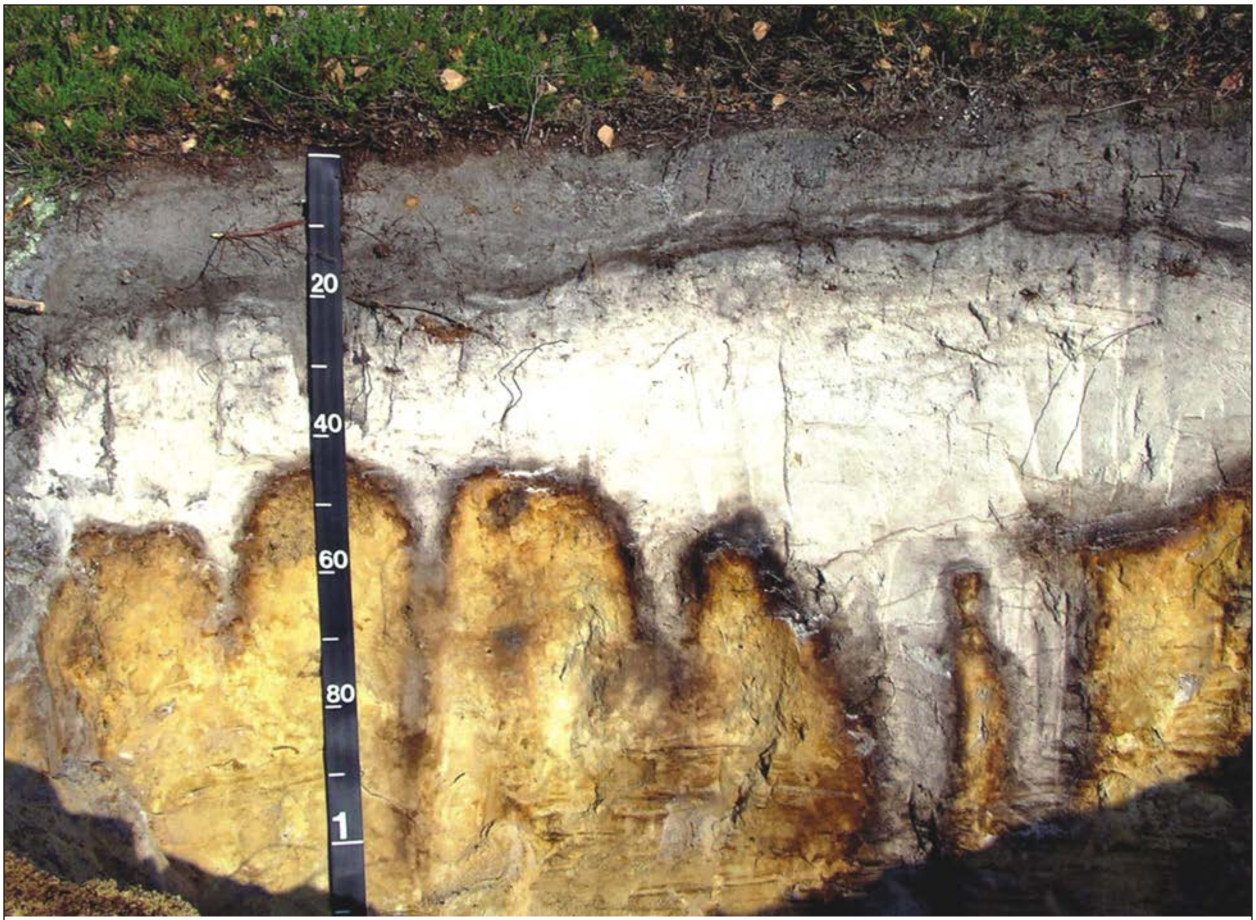

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Salinity Sensor: A Reliable Tool for Monitoring *in situ* Soil Salinity under Saline Irrigation

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Abstract: The main objective of this study was to evaluate the use of salinity sensors with other methods currently being used for monitoring *in situ* soil salinity. Salinity sensors were installed in a field experiment receiving saline irrigation water for screening salt tolerant landscape trees. Soil salinity was measured by conventional analytical procedures (saturation-paste-extract, 1:1, 1:2 and 1:5 soil-water suspension) and the salinity sensors. Soil salinity measured by salinity sensors was very close to the irrigation water salinity than the conventional analytical methods and 1-1.5 times higher than the conventional methods ($r = 0.98$). The soil salinity measured by salinity sensors truly represented the salt concentration of soil solution encountered by the growing plants. The salinity sensors proved cost effective, more practical, easily operational and reliable tool for monitoring *in situ* soil salinity under saline irrigation for increasing agricultural production. It is strongly recommended that the use of salinity sensors should be encouraged for quick results of soil salinity than the conventional methods to improve water use efficiency and also to maximize the use of saline irrigation for increasing land productivity.

Key words: Salinity sensor, soil salinity, water salinity, plant growth, plant biomass, water use efficiency, soil-water suspension

INTRODUCTION

Soil salinity is a severe environmental hazard (Hillel, 2000) that impacts the growth of many crops. Worldwide, salinization problems are spreading at a rate up to 2 million hectares a year, which offsets a good portion of the increased productivity achieved by expanding irrigation (Postel, 1999). Soil salinity affects the soil physico-chemical properties and the water availability to plants. Therefore, its accurate measurement is a key factor for developing appropriate guidelines for planning future reclamation and rehabilitation projects for salt affected lands.

Conventionally soil salinity is determined by laboratory analysis (electrical conductivity of the saturated paste extract EC_e. This procedure is expensive and time consuming and provides an incomplete view of the extent of soil salinity. An alternative to laboratory analysis to assess soil salinity in the field by determining the apparent electrical conductivity (EC_a). Nichol *et al.* (2002) stated that Dual_tangent analysis of the raw waveform is found to be more accurate than the remote diode shorting method within water solutions and within silica sand saturated with an electrically conductive water solution. Hamed *et al.* (2003) observed that the Sigma Probe (SP), which measures water content, gave accurate readings for electrical conductivity of the soil solution ouly slightly

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dependent on water content and soil type. However, Robinson *et al*. (2003) concluded that the key to Time Domain Reflectometry (TDR) success is its ability to accurately measure the permittivity of a material and the fact that there is a good relationship between the permittivity of a material and its water content. A further advantage is the ability to estimate water content and measure bulk soil EC simultaneously using TDR. Castiglione *et al*. (2006) used coaxial multiplexers to monitor up to hundreds of TDR probes through computer or data-logger interface. They observed the different probes connected to a common multiplexer or multiplexer network interfere with one another. They further mentioned that the interference did not affect the signal travel time and therefore the water content measurement, but resulted in appreciable errors in measured electrical conductivity. Lin *et al*. (2007) stated that methods acconnting for cable resistance in time domain reflectometry (TDR) base electrical conductivity measurements remained controversial and the effect of TDR recording time was underrated when long cables were used. Bieganowski (2003) used current-voltage curve interpretation, registered in the saturated soil, in categories of soil salinity evaluation. A quantity containing the information about the salinity is electrical conductivity of the soil. This conductivity could be evaluated by the analysis of the slope of a straight line, fitted into the part of the current-voltage curve, which is responsible for the reduction of hydrogen ions during electrolysis of water contained in the soil. Konukcu *et al*. (2003) in a study on soil salinity measurement indicated that thermal-conductivity probes measured water content over a wide range from saturation to 0.16 m^3 m^{-3} for clay loam and to 0.09 m^3 m^{-3} for sandy loam soil with great sensitivity (R^2>0.95) and were nnaffected by the clay accumulation. The 4-probe electrode probes provided reliable measurements (R^2> 0.95) of the salinity of the soil solution for the range relevant to agricultural application. Boutin and Martin (2006) examined the salinity variability recorded by Array for Real-Time geotropic Oceanography (ARGO) floats in the upper 10 m layer of the surface ocean. They showed that the surface salinity variability at ten days and 200 km scales is above ±0.1 psu fro 30% of the drifters and that this variability is larger than 0.2 psu in tropical regions affected by strong discharges and by precipitations and in frontal areas characterized by strong mesoscale activity. Amezketa (2006) used a mobile and geo-referenced electromagnetic sensing system to assess soil salinization at spatial and temporal scales in irrigated fields. He concluded that the development of new technologies such as electromagnetic (EM) induction sensors has revolutionized the way in which soil salinity is measured. Eldiery *et al*. (2005) described an approach to develop soil salinity maps using remotely sensed data. The approach involved integrating remote sensing data from Ikonos, GIS and special analysis. The results showed that the green band, the near infrared band and the near infrared band divided by the red band ratio are strongly related to soil salinity. Bouksila *et al*. (2008) used Time Domain Reflectometry (TDR) and the new wet WET sensor based on Frequency Domain Reflectometry (FDR) for the determination of soil water content and salinity. They fonnd that WET sensor gave similar accuracy to TDR if calibrated values of the soil parameters were used instead of standard values. Zhang *et al*. (2004) conducted laboratory tests to simultaneously measure soil water content and salinity using a four-electrode Wenner array sensor. They showed that, in general, the calibration models predicted the water content more accurately than salinity. The R^2 values for predicting water content and salinity at the 30 mm penetration depth reached 0.89 and 0.91, respectively. Whereas the root-mean-square errors for volumetric water content and salinity measurements were 0.019 m^3 m^{-3} and 0.173 cmol kg^{-1}, respectively. The determination of salinity through the use of conductivity measurements was first recognized by Kudsen (1901) but was not developed until the 1950's. AT that time, a conductivity salinometer was developed for the International Ice Patrol that was capable of measuring salinity to better than 0.01 ppt (Emery and Thomson, 1998).

Soil electrical conductivity, which is known as EC, is the ability of soil to conduct electrical current. EC is expressed in milliSiemens per meter (mS m^{-1}). Traditionally, soil paste EC has been used to assess soil salinity (Rhoades *et al*. 1989), but now commercial devices are available to rapidly and economically measure and map bulk soil EC across agricultural fields. However, EC measurements also have the potential for estimating variation in some of the soil physical properties in a field where soil salinity is not a problem. Kemper (1959) developed the first *in situ* salinity sensor. It consisted of electrodes imbedded in porous ceramic to measure the Electrical Conductivity (EC) of the solution within the ceramic cell. When placed in soil, these devices imbibe water which, in time, comes to diffusional equilibrium with the soil water. Richard (1966) improved the design of the soil salinity sensor to shorten its response time and to eliminate external electrical current paths. Austin and Rhoades (1979) developed and introduced a compact four-electrodes salinity sensor into routine agricultural practices. Relationship between electrical conductivity measured *in situ* with four-electrodes probe and conductivity of soil solution or saturated soil paste were developed (Nadler, 1981; Rhoades *et al*., 1989; Slavich and Peterson, 1990). Recent developments in EC sensors and their ability to produce EC variation maps has attracted much attention among producers about potential applications of this sensor for improving field management. Presently there are two types of EC sensors currently on the market to measure soil EC in the field. These are (1): Contact Method. This type of sensor uses electrodes, usually in the shape of coulters that make contact with the soil to measure the electrical conductivity and (2): Non-contact method: This type of sensor works on the principal of electromagnetic Induction.

The EC value is a combined result of physical and chemical properties of soil. It has potential applications in precision agriculture for management decisions and the delineation of management zones. For precision agriculture applications, EC information works best when yields are primarily affected by factors that are best related to EC, for example, water holding capacity, salinity level, depth of top soil and so on. The main objective of this study was to evaluate soil salinity measurements by conventional methods and the salinity sensors and also to develop relationship between these measurements for field application.

MATERIALS AND METHODS

The experiment was carried out at KACST research station Al-Muzahmiyia, Kingdom of Saudi Arabia from 1999-2002 where the high saline pond water (residue of RO-Plant) and the fresh groundwater were available. Treatments include Soil = 1 (Sandy), Plants = 3 (*Prosopis juliflora*, *Prosopis specigera*, *Prosopis tamarugo*), water salinity = 4 (2, 4, 8 and 12 thousand mg L^{-1}), irrigation system = 1 (Bubbler), irrigation level = 1 (Irrigation at 20% moisture depletion of field capacity) and replications = 4. Statistical Design used was a Complete Randomized Block Design. The experiment was laid out in an area of 200×30 m and divided into four blocks of equal size for the application of different water salinity treatments. The selected plants were transplanted during November, 1999. The plant to plant and row to row distance was 1 and 2 m, respectively. The initial physical and chemical characteristics of experimental soil are presented in Table 1.

Irrigation of Plants

Total amount of water for irrigation, to fulfill field capacity of soil of a plant basin measuring 1 m (diameter) and 0.5 m depth, was calculated from the soil moisture data. The total amount of irrigation water was applied on the basis of maximum water holding capacity of soil at field capacity. The irrigation was applied at 20% depletion of soil moisture at field capacity and came to 10 L $plant^{-1}$ per irrigation. All the plants received 15% excess water, above the field capacity level of soil, as leaching requirement to maintain soil salinity within acceptable limits for normal growth. Three water tanks, each having a capacity of 10 m^3, were placed near the block to apply irrigation water of desired salinity for different treatments.

Table 1: Initial physical and chemical characteristics of experimental soil

Parameters	Reading
Texture	Sand
Saturation (%)	20.00
EC_e (dS m^{-1})	1.26
pH	7.85
TDS (mg L^{-1})	810.00
Ca (mg L^{-1})	101.00
Mg (mg L^{-1})	26.00
Na (mg L^{-1})	87.00
K (mg L^{-1})	12.00
Cl (mg L^{-1})	243.00
CO_3 (mg L^{-1})	4.00
HCO_3 (mg L^{-1})	113.00
SAR	2.00

Table 2: Mean chemical composition of well water, evaporation pond water and the treatments waters

Parameters	Pond water	T_1 (Well water)	T_2	T_3	T_4
EC (dS m^{-1})	23.1	2.5	7.0	12.5	18.8
pH	7.4	7.7	7.8	8.1	7.8
TDS (mg L^{-1})	14,800.0	1,654.0	4,474.0	7,970.0	12026.0
Calcium (mg L^{-1})	1260.0	212.0	424.0	665.0	957.0
Magnesium (mg L^{-1} ppm)	665.0	59.0	216.0	336.0	497.0
Sodium (mg L^{-1})	3623.0	227.0	938.0	1755.0	2814.0
Potassium (mg L^{-1})	209.0	14.0	46.0	99.0	162.0
Chloride (mg L^{-1})	6995.0	653.0	2135.0	3926.0	5524.0
Carbonate (mg L^{-})	15.0	0.0	9.0	15.0	7.0
Bicarbonate (mg L^{-1})	143.0	152.0	150.0	118.0	112.0
SAR	20.0	3.5	10.0	15.1	20.4

Composition of Waters of Different Salinities

Waters for different salinity treatments were composed by mixing freshwater from a well having an EC of around 2.5 dS m^{-1} with the water from an evaporation pond having EC between 31-42 dS m^{-1}. The freshwater and the saline pond water were mixed in proper proportions to attain water EC of 6.25, 12.5 and 18.75 dS m^{-1} for T_2, T_3 and T_4, respectively. Freshwater from the well was kept as the control treatment. Water samples were collected from the well, evaporation pond (before composition) and irrigation tanks (after composition) and analyzed for pH, EC, Ca, Mg, Na, K, CO_3, HCO_3 and Cl. The chemical composition of the well water, pond water and the treatment waters is given in Table 2.

Installation of Tensiometers

Three sets of tensiometers (each set of two tensiometers) were installed in each block at 12 cm distance from the main trunk of a plant at 15 and 30 cm depth of soil to monitor soil moisture depletion. In all, there were 12 sets of tensiometers in 4-blocks (Fig. 1).

Installation of Salinity Sensors

Three sets of salinity sensors (each set of two) were installed in each block at 10 cm distance from the main trunk of a plant at 15 and 30 cm depth of soil to monitor soil salinity. In all, there were 12 sets of salinity sensors in 4-blocks (Fig. 1).

Plant Growth Measurements

Plant growth measurements included plant height and total biomass. Plants were harvested after completion of one year growing season. A total of two crop seasons were completed for the experiment. Fresh biomass was recorded for each plant at the time of harvesting.

Salinity sensor Tensiometers

Fig. 1: Salinity sensor and Tensiometers in the field

Soil Samples

Soil samples were taken from 0-15, 15-30 and 30-60 cm depth of soil from each plant before and after the harvesting to measure soil salinity. The soil samples were analyzed for pH, EC, SAR and physical separates (sand, silt and clay %) according to US Salinity Staff (1954).

Factors Affecting Soil Electrical Conductivity (EC)

The conduction of electricity in soil takes place through the moisture-filled pores that occur between individual soil particles. Therefore, the EC of soil is determined by the following soil properties.

- **Porosity:** The greater the soil porosity, the more easily electricity is conducted. Soil with high clay content has higher porosity than sandy soil. Compaction normally increases soil EC.
- **Water content:** Dry soil is much lower in conductivity than the moist soil.
- **Salinity level:** Increasing concentration of electrolytes (salts) in soil water will dramatically increases soil EC.
- **Cation Exchange Capacity (CEC):** Mineral soil containing high levels of organic matter (humus) and or 2:1 clay minerals such as montmorillonite, illite, or vermiculite have a much higher ability to retain positively charged ions (such as Ca, Mg, K, Na, NH_4 or H) than soil lacking these constituents. The presence of these ions in the moisture filled soil pores will enhance soil EC in the same way that salinity does.
- **Temperature:** As temperature decreases towards the freezing point of water, soil EC decreases slightly. Below freezing, soil pores become increasingly insulated from each other and overall soil EC declines rapidly.

The following dilution factors are recommended to convert 1:5 suspension EC into saturation paste extract EC for practical purpose.

Dilution factors to convert 1:5 suspension EC into saturation paste extract

Soil texture	Factor
Loamy-sand, clay-sand, sand	23
Sand-loam, fine-sandy-clay, loam-sandy-clay	14
Loam, loam-fine-sand, silt-loam, sandy-clay-loam	10
Clay-loam, silty-clay-loam, fine-sandy-clay-loam, Sandy-clay, silty-clay, loamy-clay, loamy-medium-clay	9
Medium clay	8
Heavy-clay	6

Source: Slavich and Petterson (1990)

The data were subjected to statistical analysis according to Snedecor and Cochran (1973).

RESULTS

Prosopis juliflora

Plant Fresh Biomass

Mean biomass per plant ranged between 8.2-11.2 kg in various water salinity treatments (Table 3). The biomass yield increased significantly with increasing water salinity than the control treatment ($\text{LSD}_{0.05} = 1.042$). The difference in yield was significant among all the treatments except T_1 and T_2 where it was not significant. The trend of increase in biomass for the effect of irrigation water salinity was almost similar in both the growing seasons. This increasing trend could be due to the fact that the plant, being semi to high salt tolerant might have utilized the mineral elements from irrigation water to meet its nutritional requirements. Since Prosopis juliflora belongs to the leguminous family, it might also have fixed some of the atmospheric nitrogen which countered the adverse effects of high irrigation water salinity thus resulting in better growth under saline irrigation.

Prosopis specigera

Plant Fresh Biomass

Mean biomass per plant ranged between 0.7-1.3 kg in various water salinity treatments (Table 3). The biomass yield increased significantly up to water salinity of 4,000 mg L^{-1} and then decreased significantly with increasing water salinity than the control treatment ($\text{LSD}_{0.05} = 0.242$). The difference in yield was significant between T_1 and T_4, but it was not significant among T_1, T_2 and T_3 treatments. The data further show that increase in irrigation water salinity to a certain level supported the plant growth but later on it adversely affected the plant growth. The trend for the effect of irrigation water salinity was similar in both the growing seasons.

Prosopis tamarugo

Plant Fresh Biomass

Mean biomass per plant ranged between 0.3-0.6 kg in various water salinity treatments (Table 3). The biomass yield showed significant increases up to water salinity of 4,000 mg L^{-1} and then decreased significantly with increasing water salinity than the control treatment ($\text{LSD}_{0.05} = 0.228$). The difference in yield was not significant between T_1 and T_2 and among T_1, T_3 and T_4 treatments. The data further show that increase in irrigation water salinity to moderate level supported the plant growth but above that it adversely affected the plant growth.

Soil Salinity

Depending upon different irrigation water salinity treatments, mean soil salinity ranged between 3.59-18.26 dS m^{-1} in the surface 0-15 cm and 4.33-21.33 dS m^{-1} in the sub-surface 15-30 cm depth of soil (Table 4). The soil salinity increased significantly with the application of waters of different salinities and seemed approaching to equilibrium with the irrigation water salinity.

Table 3: Effect of irrigation water salinity on biomass yield of plants

	BM (kg plant^{-1})		
Treatments	*Prosopis juliflora*	*Prosopis specigera*	*Prosopis tamarugo*
T_1	8.20c	1.1a	0.4ab
T_2	8.40c	1.3a	0.6a
T_3	10.05b	1.0a	0.3b
T_4	11.24a	0.7a	0.3b

Figures in a column followed by the same letter(s) are not significantly different at 5% level of significance, BM = Biomass

Table 4: Mean soil salinity recorded by salinity sensors

	Soil depth (cm)		
Treatments	0-15	15-30	0-30
T_1	3.59	7.01	5.30
T_2	11.31	11.34	11.33
T_3	18.47	17.32	17.90
T_4	18.26	21.23	19.75

Table 5: Effect of saline irrigation treatments on EC_e

		After first harvesting		After second harvesting	
Treatments	Pre-study EC_e (dS m^{-1})	EC_e (dS m^{-1})	Increase over pre-study (%)	EC_e (dS m^{-1})	Increase over pre-study (%)
T_1	1.26	1.90	151	3.54	281
T_2	1.26	3.62	287	5.62	446
T_3	1.26	5.17	410	9.74	773
T_4	1.26	7.81	620	9.95	710

Laboratory Measurements

Mean soil salinity ranged between 1.9-7.81 dS m^{-1} (First Year) and 3.54-9.95 dS m^{-1} (Second Year) in different water salinity treatments (Table 5). The soil salinity increased significantly with increasing irrigation water salinity than the control (TDS of water = 2,000 mg L^{-1}) treatment. The difference in soil salinity was significant among all the treatments except for the second growing season where it was not significant between T_3 and T_4 treatments. Overall percent increase in soil salinity ranged between 151-620% after first harvesting and 281-773% after second harvesting. This also indicated that salt build up in soils depends on the total water salinity and the time period over which the land remained under irrigation.

Soil salinity measured by salinity sensors was significantly higher than the conventional methods. This might be due to the fact that the soil solution around plant root zone contain maximum amount of dissolved salts upon irrigation. Whereas, in the laboratory, the soil saturation paste extract is prepared which is kept overnight and then the soil salinity is measured which might have diluted the salts and depicted low values than *in situ* measurements. In conclusion, the salinity sensors proved a better tool for monitoring soil salinity under field conditions in the vicinity of roots of the growing plants than the conventional laboratory methods. Moreover, *in situ* soil salinity measurement technique is less destructive to soil and plants, needs less time for taking observation and is cost effective.

Relationship Between EC_w vs EC_e and EC_s

A regression analysis was run to determine relationship between EC_w and the soil salinity measured by soil saturation paste extract and salinity sensors (Fig. 2). The soil salinity measured by salinity sensors is closely related to the irrigation water salinity as compared to EC of saturated paste

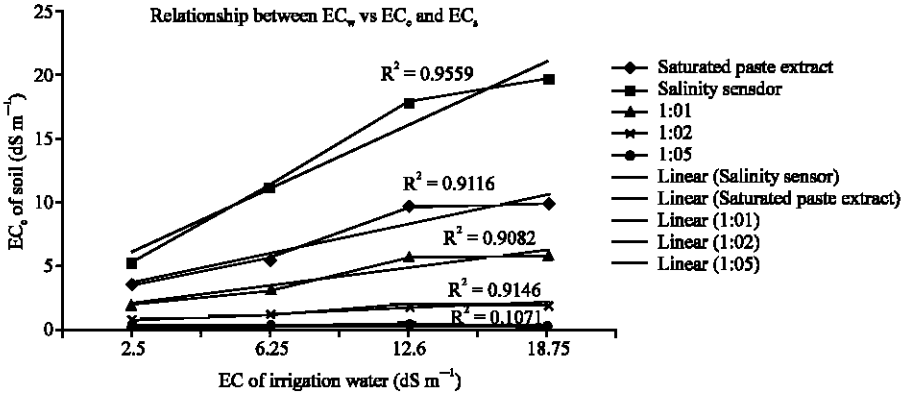

Fig. 2: Comparison of EC_e values for different analytical methods

extract. This indicates that *in situ* soil salinity measurements were better indicators of the actual solute potential around plant roots than EC_e. As such, the use of salinity sensors should be preferred over other time consuming methods

DISCUSSION

Presently many conventional methods and quick techniques are being used for accurate measurement of soil salinity under saline irrigation practices. The study findings indicated that the soil salinity measured by salinity sensors was very close to the irrigation water salinity and 1-1.5 times higher than that obtained by the conventional methods. The research findings agree with those of Bouksila *et al.* (2008), Amezketa (2006), Zhang *et al.* (2004), Konukcu *et al.* (2003), Hamed *et al.* (2003), Robinson *et al.* (2003) and Nichol *et al.* (2002) who concluded that soil salinity sensors and salinity probes were better, quick and accurate in determining the soil salinity than the conventional methods for better understanding salt accumulation in saline irrigated soils in order to reduce crop yield losses.

CONCLUSIONS

Soil salinity increased significantly with the application of saline water, but the application of 15% leaching requirements prevented soil salinity development to a greater extent. Mean fresh biomass of all plants decreased significantly with increasing irrigation water salinity except *Prosopis juliflora*, which showed increases in fresh biomass with increasing irrigation water salinity. Contrastingly, *Prosopis specigera*, showed increases in biomass with water salinity between 4000 and 8000 mg L^{-1} but showed decreasing trend above this limit. Whereas, *Prosopis* tamarugo showed continuous decrease in biomass with increasing irrigation water salinity.

Salinity sensors proved a reliable tool for measuring *in situ* soil salinity than the conventional laboratory methods which are laborious and time consuming. Also, the tensiometers did not prove a reliable equipment for monitoring soil moisture in coarse textured (sandy) soils.

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