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Salination of Organic Soils in the Sacramento-San Joaquin Delta of California*

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Summary. The Delta is an important agricultural area containing organic soils that are threatened by salinity. To aid in water allocation and management decisions, the maximum salinity level in irrigation water that preserves agricultural production was estimated from data gathered in a field trial to establish the salt tolerance of corn. All of the physical properties measured indicated that the soil under study was typical of organic soils in the Delta and elsewhere. Differences in soil sample preparation were shown to influence salinity measurements from the subsoil. Samples brought to saturation without either grinding or drying gave electrical conductivity measurements in agreement with those for soil water extracted by suction cups. Above average rainfall and water table control during the winter effectively leached the upper soil profile. The ratio between the average electrical conductivity of the soil water in the root zone ($\overline{EC}_{sw}$) and the salinity of the irrigation water (EC_i) was found to be a function of EC_i and not constant. Under present conditions of low EC_i (0.2 to 0.8 dS/m) and with normal winter rainfall $\overline{EC}_{sw}/EC_i$ is about 8. As EC_i increases, however, the ratio decreases. At the soil water salinity threshold for corn grain (3.7 dS/m), the average ratio is 1.7 which results in a maximum value of 2.2 dS/m for EC_i without yield loss under normal conditions. With subirrigation and below normal rainfall, as in 1981, the maximum value of EC_i would be 0.8 dS/m.

Introduction

Significant concentrations of soluble salts are not normally found in organic soils. Organic soils, differentiated from mineral soils by an organic matter content in excess of 20%, are formed from partially decayed plant remains which accumulated originally in bodies of fresh water or in poorly drained areas where anaerobic conditions persisted. In contrast, saline soils usually occur in regions where water is

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lacking. As the demand for water intensifies, water conservation improves, or the use of degraded water increases, the salt concentration of irrigation water will increase. Thus, irrigated organic soils may be threatened by excess salinity, particularly during droughts.

The Sacramento-San Joaquin Delta is an important example of an agricultural area with organic soils that are threatened by salinity. Although an average of nearly 28 km^3 of fresh water pass through the Delta annually (California State Water Resources Control Board 1978), two major water distribution systems make withdrawals from the Delta for use elsewhere in California. If water withdrawals become excessive, the salt concentration of the remaining surface waters will increase as water within the Delta is reused and as seawater, intruding by tidal action from San Francisco Bay, mixes with the fresh water. If the surface waters become degraded, continued irrigation of the 50,000 ha of organic soil in the Delta will lead to salination.

To determine the maximum salt level in the surface waters that can sustain full agricultural production in the Delta, a 3-year field experiment was conducted to establish the salt tolerance of corn, an important, salt-sensitive crop. The experimental results (Hoffman et al. 1983) indicated that maintaining the average electrical conductivity of the soil water (EC_{sw}) in the root zone below 3.7 dS/m (decisiemens/meter = mmho/cm) prevented loss in corn production from soil salinity. With the establishment of this limit, the major question remaining is the relationship between the salinity of the surface waters in the Delta and soil water salinity. Unfortunately, this relationship is complex and is influenced by a number of factors that include soil properties, rainfall, and management practices, including irrigation and leaching.

The primary objective of this project was to establish the relationship between the salinity of irrigation water and soil water salinity for the organic soils of the Delta. This was pursued in a series of individual studies. First, we determined the extent to which the soil at the experimental site (Hoffman et al. 1983) was representative of the organic soils of the Delta. Next, we evaluated the reliability of different procedures for measuring soil salinity in organic soils. We then determined the relationship between soil salinity and salinity of the irrigation water as reported by Hoffman et al. (1983). Finally, we considered the extent to which this relationship between soil and irrigation water salinities is applicable throughout the Delta.

Physical Soil Properties

The soil at the field experiment was Rindge muck (*Typic medisaprist,* euic, thermic) which is typical of organic soils in the Delta. With depth, the soil changes from muck to peat and then to a comparatively impervious mineral substrata. The remains of plants predominate in the black upper soil layers with organic matter content, expressed as the per cent of the total soil mass lost by incineration at 550 °C for 2 hours, averaging 45% near the surface (Table 1). The peat layer below consists of dark, coarse, fibrous plant residues with an organic matter content approaching 60%. Other organic soils in the Delta have organic matter contents

Table 1. Properties of Rindge muck

Soil Depth cm	Organic Matter %	Bulk Density Mg/m^3	Saturated Volumetric Water Content m^3/m^3	Saturated Gravimetric Water Content kg/kg
15	45	0.70	–	–
30	47	0.56	0.64	1.2
45	53	0.47	–	–
60	57	0.29	0.79	2.9
90	59	0.21	0.85	3.7
120	–	0.19	0.90	6.3

ranging from 25 to 55% shallow in the profile to 40 to 75% in the subsoil (Campbell and Richards 1950). In comparison, the organic soils of the Hula Basin in Israel, although deeper, range in organic matter from 33% near the surface to over 60% in the subsoil (Dasberg and Neuman 1977).

The bulk density of Rindge muck decreases rapidly from about 0.7 Mg/m^3 near the soil surface to about 0.3 Mg/m^3 at a depth of 60 cm (Table 1). At about this depth the soil begins to change from a well-mixed, decomposed muck to undecomposed, fibrous peat. Below this transition zone, the peat with a bulk density of about 0.2 Mg/m^3 extends to a mineral substrata at an average depth of 1.8 m. Bulk density is high near the surface (but only about half that of a mineral soil), because mineral particles have accumulated in the tilled layer as organic material was lost by oxidation. In Israel's Hula Basin, the bulk density also drops from 0.7 Mg/m^3 to about 0.2 with depth (Dasberg and Neuman 1977). The bulk density of peat in the Beverly Swamp of Minnesota is 0.2 Mg/m^3 (Munro 1982).

Organic soils are characterized as having a high water-holding capacity. Rindge muck is no exception. The saturated volumetric (θ_s) and gravimetric (w_s) water contents for undisturbed soil cores as a function of soil depth are given in Table 1. These saturated water content values are averages of six undisturbed cores taken at each depth and saturated slowly from the bottom. On a volumetric basis, water content varied from 0.64 m^3/m^3 at a depth of 30 cm to 0.90 at the 120-cm depth; w_s changed from 1.2 to 6.3 kg/kg over the same depth interval. The values of w_s agree with values reported by Campbell and Richards (1950) for other organic soils of the Delta. Boelter (1964) found θ_s of decomposed peat from a Minnesota bog to vary from 0.8 to 0.9 m^3/m^3. The porosity of Hula Basin soils, equivalent to θ_s, varied from 0.67 m^3/m^3 shallow in the profile to more than 0.9 with depth (Dasberg and Neuman 1977).

The relationship between volumetric soil water content and soil matric potential is given in Fig. 1 for soil depths of 30 and 60 cm. The matric potential values were obtained from tensiometer readings and water contents were determined with a neutron probe (Hoffman et al. 1983). Data are given for both sprinkled and subirrigated treatments. The curves through the data were calculated from the model of van Genuchten (1980) which requires only the saturated volumetric water content (Table 1) and air-dry water content (assumed to be 0.2 m^3/m^3) for the soil to predict the relationship. Agreement between data and model is excellent, even

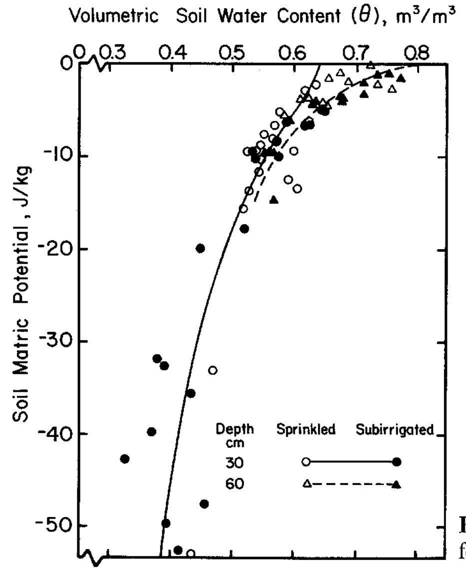

Fig. 1. Moisture release curve for Rindge muck for two soil depths

though the model was developed for mineral soils. The curve is well within the range of moisture release curves reported for other Delta organic soils (Campbell and Richards 1950).

The physical properties of Rindge muck appear to be representative of organic soils found in the Delta as well as elsewhere. Values for each property measured are well within the range of published values. Thus, conclusions formulated on salination from this experiment that are dependent on physical properties should be indicative of results to be expected in organic soils from this and other areas.

Soil Sample Preparation Effects on Measured Soil Salinity

It is imperative that the preparation procedure most indicative of the salinity level to which the crop is responding be used for monitoring soil water salinity. Previous projects to monitor salinity in the organic soils of the Delta indicated that sample preparation influenced the measured electrical conductivity, particularly in the subsoil (unpublished results of B. R. Hanson and A. B. Carlton 1980). Before measuring the electrical conductivity of a soil saturation extract (EC_e), the soil sample may be either dried, ground, and passed through a 2-mm round hole sieve or passed through a sieve without drying or grinding. Water is then added while mixing until the soil is saturated. The mixture is allowed to stand overnight and additional water is added if required to saturate the sample. The *EC* of a water sample extracted by vacuum from the saturated soil is then measured.

In September 1979 soil samples were taken from each experimental plot (Hoffman et al. 1983) at depth intervals of 0 to 15, 15 to 30, 30 to 45, 45 to 60, and 60 to 90 cm. Before analysis, each sample was divided into three subsamples. One set of subsamples was allowed to dry at room temperature and then ground (dry,

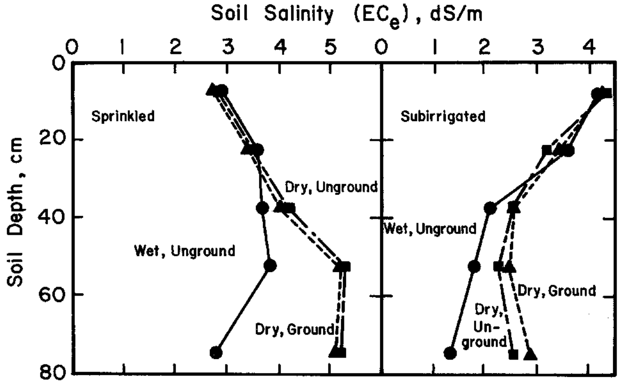

Fig. 2. Influence of soil sample preparation technique on resultant value of the electrical conductivity of the soil saturation extract (EC_e). Data are for 2.0 dS/m irrigation treatments sampled in September 1979

ground). A second set was dried at room temperature but was not ground (dry, unground). The third set was brought to saturation without drying or grinding (wet, unground). All of the subsamples were analyzed for gravimetric field water content (w), gravimetric water content at saturation prior to extraction (w_e), electrical conductivity of the soil saturation extract (EC_e), calcium plus magnesium (Ca + Mg), sodium (Na), chloride (Cl), sulfate (SO_4), and boron (B).

The influence of sample preparation on EC_e is illustrated in Fig. 2 for samples taken from the salinity treatments with applied waters having an EC of 2 dS/m for the two irrigation methods tested. Sample preparation had no significant influence on EC_e from samples collected above a depth of 30 cm. Below 30 cm, significant differences occurred between dried and undried samples. Grinding had little

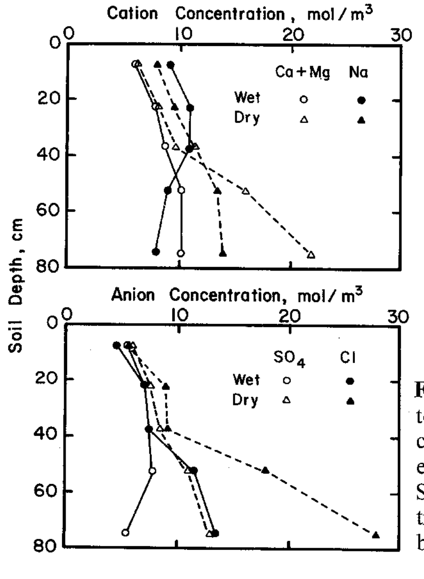

Fig. 3. Influence of the soil sample preparation technique on the resultant cation and anion concentrations. Data points are the average values for each ion for all salinity treatments sampled in September 1979 and prepared by wetting to saturation without drying (wet) or with drying (dry) before saturation

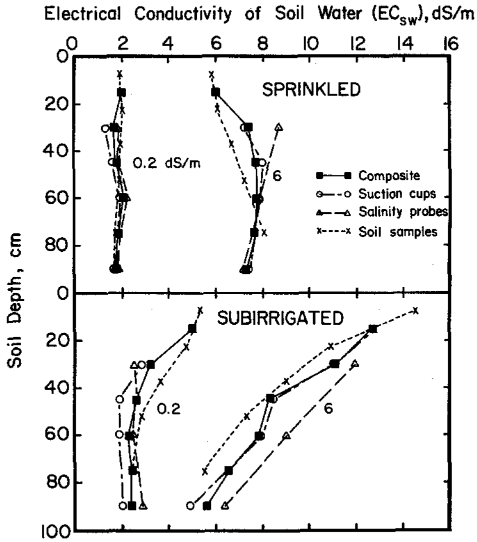

Fig. 4. Examples of the relationships among time-weighted averages of the electrical conductivity of soil water from suction cups, salinity probes, and soil samples (wet, unground), and the composite averages of these data. Examples are for the 0.2 and 6 dS/m salinity treatments for 1981

influence on the results, but drying the sample before analysis resulted in significantly higher values of ion concentration compared with undried samples for depths below about 30 cm (Fig. 3).

The soil salinity values from undried samples were compared with direct measurements on soil water with suction cups and in situ measurements with four-electrode salinity probes (Rhoades 1979). For these comparisons the EC_e values from the undried soil samples were adjusted for water content by the relationship $\overline{EC}_{sw} = (\theta_s w_e)/(\theta w_s\, EC_e)$, where θ is the volumetric field water content determined with a neutron probe. Examples of measurements of $\overline{EC}_{sw}$ by the various techniques are given in Fig. 4 for the salinity treatments receiving irrigation waters having EC's of 0.2 and 6 dS/m for both irrigation methods during 1981. Obviously, measurements of $\overline{EC}_{sw}$ from wet, unground soil samples agree well with the other measures of soil salinity.

Relationship between Irrigation Water Quality and Soil Salinity

Irrigation water quality has a dominant influence on soil salinity; however, winter rainfall, soil properties, leaching practices, irrigation techniques, and the elevation and salt concentration of a water table can significantly influence the relationship. The relationship between the electrical conductivity of the irrigation water (EC_i) and the average electrical conductivity of soil water in the root zone ($\overline{EC}_{sw}$) for the field experiment is given in Fig. 5 for each year and for subirrigated and sprinkled methods. An average of EC_{sw} for each soil depth monitored by suction cups, four-electrode salinity probes, and soil samples, was utilized to determine a composite average of $\overline{EC}_{sw}$ for each 15-cm soil increment through the root zone to a depth of 90 cm. These composite values (see Fig. 4 for examples) were averaged to establish $\overline{EC}_{sw}$ (Hoffman et al. 1983). It is possible that an alternate method of calculating $\overline{EC}_{sw}$

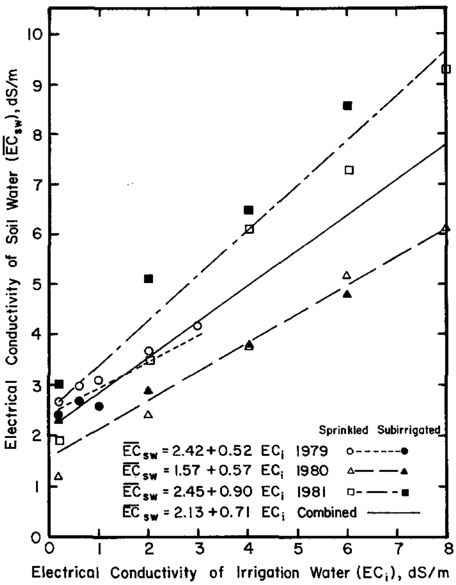

Fig. 5. Relationship between the salinity of the irrigation water and the average salinity in the root zone for the field trial

might result in some minor changes in $\overline{EC}_{sw}$. The relationship for all the data combined is shown as a solid line. The largest influence on the relationship, however, occurred among years not irrigation method. This was caused, in large part, by differences in winter rainfall and management of the water table depth.

Of particular importance is the projected relationship between EC_i and $\overline{EC}_{sw}$ as EC_i increases (Fig. 5). For 1981, the year when the influence of EC_i on $\overline{EC}_{sw}$ was the greatest, the slope was 0.9. Thus, increasing the salinity of the irrigation water above 0.2 dS/m should only increase the average soil salinity in the root zone by a similar amount if winter rainfall is typical and irrigation, leaching, and groundwater control practices are similar to those for the subirrigated treatments of the field experiment (Hoffman et al. 1983). From the general relationship given in Fig. 5, the electrical conductivity of the irrigation water that would result in a soil water salinity equivalent to the threshold value for corn grain (3.7 dS/m, Hoffman et al. 1983) would be 2.2 dS/m. For below normal rainfall as in 1981; the EC_i resulting in the threshold value for grain would be 1.4 dS/m. For subirrigation in 1981, the worst case studied, $\overline{EC}_{sw}=2.89+0.99\ EC_i$ and the resultant EC_i for the threshold would be 0.8 dS/m.

In an environmental impact report on the Delta (State Water Resources Control Board 1978), $\overline{EC}_{sw}$ was reported to be increased five to ten times (average of 7.5) above EC_i in organic soils; i.e., $\overline{EC}_{sw}=7.5\ EC_i$. This relationship was measured in a number of fields in the Delta where EC_i probably averaged 0.3 dS/m. Thus, the expected $\overline{EC}_{sw}$ based on the earlier report would be just over 2 dS/m. This value is essentially the average value of $\overline{EC}_{sw}$ found in this field trial when EC_i=0.2 dS/m (Fig. 5). Based on the results of the present study, the ratio $\overline{EC}_{sw}$ to EC_i is not constant, but decreases as EC_i increases. Figure 6 gives the relationship of $\overline{EC}_{sw}/EC_i$ as a function of EC_i as determined from the field study results presented in Fig. 5.

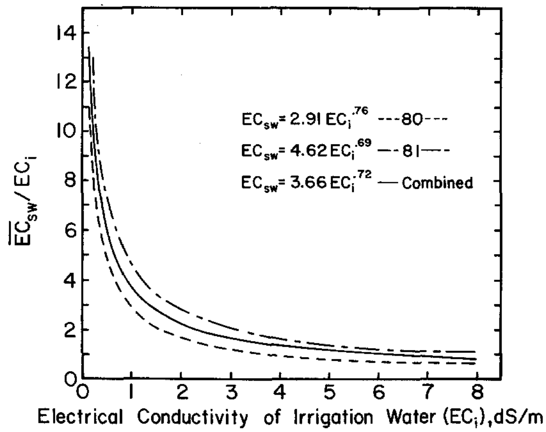

Fig. 6. Experimentally determined ratio of the average electrical conductivity of the soil water in the root zone ($\overline{EC}_{sw}$) to the electrical conductivity of the irrigation water (EC_i) as the salinity of the irrigation water changes

Soil Salinity During the Last Decade

In a separate, unrelated study, average values of soil salinity within 90 cm of the soil surface were monitored from 1973 to 1981 at three different locations in the Delta. The results are summarized in Fig. 7. Salinity was measured as EC_e on soil samples taken in the spring and fall of each year. The EC_e measurements were made on dried and ground samples and the values corrected for soil water content to give $\overline{EC}_{sw}$ values.

The "not-farmed" site is the historic area of the Western Pacific Railroad at Terminous. $\overline{EC}_{sw}$ of this site fluctuated between 1.5 and 3.7 dS/m during the study period. The highest value occurred in the spring of 1981 following the below normal annual rainfall of only 260 mm. During the 1979–80 winter when 515 mm of rain fell, $\overline{EC}_{sw}$ dropped from 3.5 to 2.2 dS/m. The asparagus site was never irrigated but the grower maintained the water table at a depth of 45 to 60 cm below the soil surface. From 1973 through 1976 soil salinity increased steadily, reaching a value of 3 dS/m. As on the "not-farmed" site, winter rainfall in 1979–80 was very effective in reducing soil salinity. After the asparagus was removed in 1980, the grower leached the field which reduced soil salinity to 1.6 dS/m in the spring of

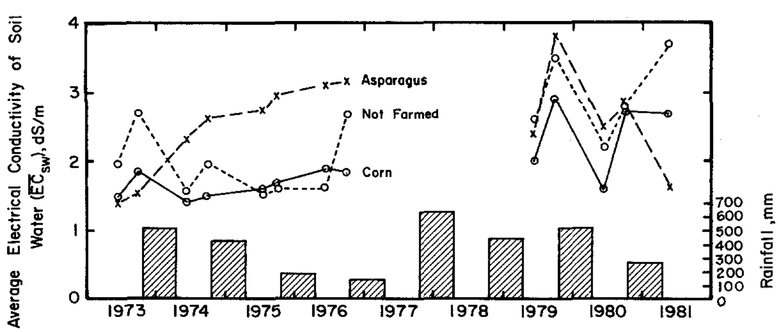

Fig. 7. Average salinity in the upper 90-cm soil profile at three sites in the Delta and winter rainfall from 1973 to 1981

1981. Soil salinity at the corn site was steady from 1973 to 1977, varying between 1.4 and 1.9 dS/m. As observed on the other sites, the 1979–80 rainfall was very effective in reducing salinity. The overall average of soil salinity at the corn site was 1.9 dS/m. This value is comparable to the average value of 2.2 dS/m for the control treatments in the field trial (Fig. 5). This comparison adds credence to the relationship of $EC_{sw}=7.5\ EC_i$ when EC_i is approximately 0.2 dS/m.

Effects of Winter Rainfall on Soil Salinity

The organic soils of the Delta are normally drained by pumps that stabilize and control the water table. Excess water is collected in a network of open drains and lifted into the leveed water channels by drainage pumps. Drainage is most critical early in the spring when the increased water table elevation from winter rainfall must be lowered for planting. In the Delta almost all of the significant amounts of rainfall during the winter and are generally permitted to add to the elevation of the water table until spring. Winter rainfall reduces soil water salinity by dilution and by any leaching which occurs as the water table is lowered. In the field experiment, the effect of winter rainfall was monitored from measures of soil salinity taken by soil samples in the fall and again the following spring.

During the first year of the field trial the maximum salinity treatment was an EC_i of 3 dS/m. In the winter of 1979–80, 515 mm of rain fell. Normal rainfall is about 360 mm. Because of the low salinity level in the irrigation water and high rainfall, the salinity that had been added during 1979 was leached. In subsequent years, EC_i's as high as 6 dS/m were used for both sprinkled and subirrigated treatments. Only 260 mm of rain fell during the winter of 1980–81; well below seasonal average. As a consequence, rainfall had little effect on reducing soil salinity in the subirrigated treatments (Fig. 8) and EC_e in the upper root zone of the sprinkled treatments dropped less than 3 dS/m, while salinity at the bottom of the root zone increased slightly. Rainfall during the winter of 1981–82 was 685 mm

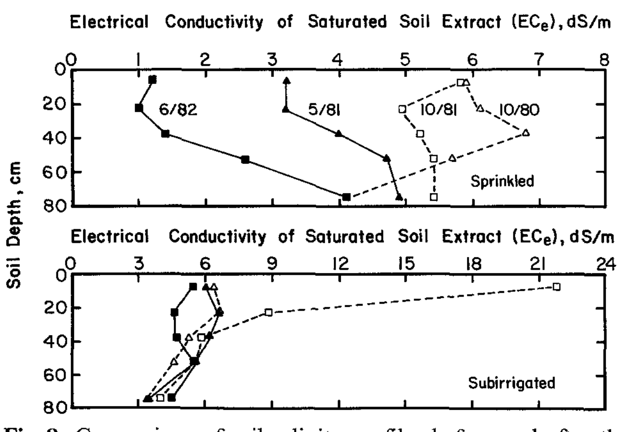

Fig. 8. Comparison of soil salinity profiles before and after the winter rains of 1980–81 and 1981–82. Profiles are for the treatments irrigated with water having an electrical conductivity of 6 dS/m for both sprinkled and subirrigated methods

and it was very effective in leaching salts from both the sprinkled and subirrigated treatments to a depth of about 60 cm. From these limited data, it appears that above normal winter rainfall can be effective in leaching organic soils, especially if the water table is controlled.

Conclusion

All of the physical properties measured indicated that the soil at the field trial was typical of organic soils in the Delta and elsewhere. Organic matter content increased from 45% near the soil surface to nearly 60% in the subsoil. Bulk density decreased with depth from 0.7 Mg/m^3 to about 0.2 Mg/m^3. Volumetric water content at saturation increased from 0.64 m^3/m^3 at the 30-cm depth to 0.90 m^3/m^3 below 1 m.

Differences in sample preparation techniques were found to influence measurements of soil salinity in subsoil samples. Measurements of electrical conductivity on samples brought to saturation without either grinding or drying agreed best with more direct measures of soil salinity.

Rainfall during the winter had a significant impact on soil salinity. Above average rainfall combined with water table control rainfall effectively leached the upper soil profile.

The ratio between the salinity of the irrigation water and the resultant soil salinity was found to be a function of the salinity of the irrigation water and not constant for the organic soils of the Delta. With the present low EC_i conditions (0.2 to 0.8 dS/m) and normal winter rainfall, $\overline{EC}_{sw}/EC_i$ was about 8 as previously reported. As EC_i increased, however, the ratio of $\overline{EC}_{sw}/EC_i$ decreased. Under present conditions in the Delta and normal rainfall, it is estimated that an EC_i of 2.2 dS/m is the maximum value of EC_i that will sustain maximum yields of corn. With subirrigation and below normal rainfall, as in 1981, the maximum value of EC_i would be 0.8 dS/m.

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