Chapter 8 Management Aspect for Crop Production

8.1 Analysis of Crop Salt Tolerance Data

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8.1.1 Introduction

Loss of crop productivity from excess soil salinity is a worldwide problem. In arid and semi-arid regions salinity is a continual threat; but even in humid areas salinity is a hazard when irrigating with brackish water or treated sewage effluent, or because of seawater intrusion. Although soil salinity can sometimes be moderated by applying appropriate water management practices, adverse levels of soil salinity are often difficult to prevent because of a lack of nonsaline irrigation water or because of other physical constraints.

Where salinity is a hazard, an effective use of available soil and water resources dictates the production of agricultural crops that are relatively salt-tolerant. For this purpose, numerous field and laboratory experiments have been conducted in order to determine the yield response to various levels of soil salinity for many crops. This has resulted in the publication of extensive salt tolerance lists by this laboratory (US Salinity Laboratory Staff 1954, Bernstein 1964, Maas 1983) and other institutions (Harris and Pittman 1919, van den Berg 1950, De Forges 1970). Unfortunately, accurate and reliable salt tolerance data are not easily obtained; they generally require elaborate and time-consuming field trials. Because of the time, labor and money involved, the number of experimental data points available for constructing a salt tolerance response function is generally limited. Moreover, the observed data frequently reflect some type of experimental variability. This makes it important to have an accurate statistical method for determining the response function.

Until recently, yield response functions to soil salinity have been either eye-fitted to the data or obtained with linear regression techniques. In an attempt to fit a generalized response function to all salt tolerance data, Maas and Hoffman (1977) published a comprehensive analysis based upon an extensive review of the literature. In general, they found that crops tolerate increases in soil salinity up to a threshold level, above which yields show an approximately linear decrease as salt concentration continues to increase. The analysis for each experiment was based upon a linear least-squares equation for values beyond the threshold salinity. In some cases, subjective judgement was required to include or exclude data from the analysis. This was particularly true when determining the threshold value.

In: I. Shainberg and J. Shalhevet (eds.), Soil Salinity under Irrigation, Processes and Management. Ecological Studies 51. Springer Verlag, New York. 1984. pp. 258-271.

The type of linear response model used by Maas and Hoffman (1977) can be characterized mathematically by a piecewise linear response function that contains two independent parameters: the salinity threshold (c_t), being the maximum soil salinity without yield reduction as compared to the yield under nonsaline control conditions, and the slope (s) of the curve determining the fractional yield decline per unit increase in salinity beyond the threshold. In equation form:

$$Y_r = \begin{cases} 1 & 0 \leqq c \leqq c_t \\ 1 - s(c - c_t) & c_t < c \leqq c_0, \\ 0 & c > c_0 \end{cases} \tag{1}$$

where Y_r is the relative yield, c is the average root zone salinity, c_t is the threshold concentration, c_0 is the concentration beyond which the yield is zero, and s is the absolute value of the slope of the response function between c_t and c_0. Soil salinity can be expressed in terms of concentration, osmotic potential, or electrical conductivities of either the soil water (EC_{sw}) or the soil saturation extract (EC_e).

Equation (1) is formulated in relative terms; the absolute yield function is given by

$$Y = \begin{cases} Y_m & 0 \leqq c \leqq c_t \\ Y_m - Y_m s(c - c_t) & c_t < c \leqq c_0, \\ 0 & c > c_0 \end{cases} \tag{2}$$

where Y_m is the yield under nonsaline conditions, and $Y = Y_r Y_m$. Figure 1 gives a schematic representation of Eq. (2). Note that the response function is continuous and consists of three piecewise linear curves and that there are now three independent parameters: c_t, s and Y_m.

To improve the analysis of Maas and Hoffman (1977), Feinerman et al. (1982) proposed a switching regression method to estimate the coefficients that appear in a two-piece linear response curve. Unfortunately, their method is restricted to those data sets that have at least two points to the left and at least three data

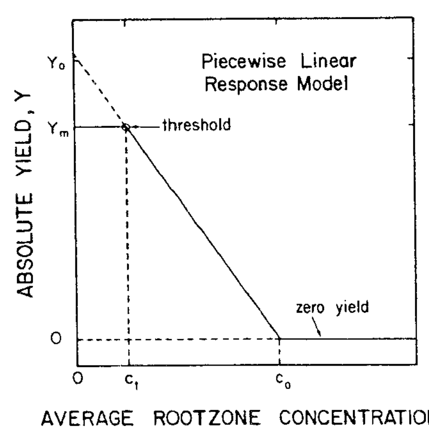

Fig. 1. Graphic representation of the piecewise linear salt tolerance response function [Eq. (2)]

points to the right of the fitted threshold value. This makes the method less suitable for experiments with a limited number of data points.

In this chapter we present some of our results with a more general nonlinear least-squares inversion method. A relatively simple computer program was written, coupling one of several salt tolerance response models with an existing nonlinear least-squares optimization method. The nonlinear least-squares model used is a simplification of a more general program described by Daniel and Wood (1971). The technique uses the maximum neighborhood method of Marquardt (1963), which is based on an optimum interpolation between the Taylor-series method and the method of steepest descent. The program has been documented in a recent research report (van Genuchten 1983) and is available from the authors. A brief description of the program is given below. Examples from the salt tolerance literature are presented in order to illustrate the various program options.

8.1.2 The Computer Program

For convenience in analyzing different types of salt tolerance data sets, 20 numbered options (NOPT) have been included in the computer program. These options relate to the choice of a particular salt tolerance response function [Eq. (2) or alternative models], and to the type and number of model parameters that are fitted to the data. Table 1 gives a list of the available options.

Table 1. Brief listings of the 20 different program options (NOPT) which include the number of unknown parameters (NP), and associated equation

NOPT	NP	Equation	Modeldescription
1	2	3	Linear regression with two unknowns (c_t and s)
2	1	5	Linear fit of s; Y_m and c_t are fixed
3	2	2	Nonlinear fit of s and Y_m c_t is fixed
4	2	2	Nonlinear fit of c_t and s; Y_m is fixed
5	3	2	Nonlinear fit of c_t and s and Y_m
6	4	2	Nonlinear fit of c_t, s and Y_m^1, Y_m^2
7	5	2	Nonlinear fit of c_t, s and Y_m^1, Y_m^2, Y_m^3
8	6	2	Nonlinear fit of c_t, s and $Y_m^1, \ldots, Y_m^4$
9	7	2	Nonlinear fit of c_t, s and $Y_m^1, \ldots, Y_m^5$
10	8	2	Nonlinear fit of c_t, s and $Y_m^1, \ldots, Y_m^6$
11	2	6	Nonlinear fit of c_{50} and p; Y_m is fixed
12	3	6	Nonlinear fit of c_{50}, p and Y_m
13	4	6	Nonlinear fit of c_{50}, p, Y_m^1, and Y_m^2
14	5	6	Nonlinear fit of c_{50}, p, Y_m^1, Y_m^2 and Y_m^3
15	6	6	Nonlinear fit of c_{50}, p, and $Y_m^1, \ldots, Y_m^4$
16	7	6	Nonlinear fit of c_{50}, p, and $Y_m^1, \ldots, Y_m^5$
17	8	6	Nonlinear fit of c_{50}, p, and $Y_m^1, \ldots, Y_m^6$
18	2	7	Nonlinear fit of α and β; Y_m is fixed
19	3	7	Nonlinear fit of α, β and Y_m
20	2	7	Nonlinear fit of β and Y_m ($\alpha = 0$)

When NOPT = 1, a simple linear regression analysis of the type

$$Y = Y_0 - s_1 c \tag{3}$$

with two unknown parameters (Y_0, s_1) is performed. Application of this option assumes that an independent estimate of Y_m is available, and hence that the data are already normalized into relative yield fractions. This method can be applied only to data points that are located between c_t and c_0 [see Eq. (2)]. Once the regression based on Eq. (3) is carried out, the salinity threshold and slope can be calculated with the expressions

$$c_t = (Y_0 - Y_m)/s_1 \quad \text{and} \quad s = s_1/Y_m . \tag{4}$$

For NOPT = 2, both Y_m and c_t are assumed to be known, thus only the slope (s) is left to be calculated from the experimental data. In this case, s is obtained from the simple equation

$$s = \sum_{i=1}^{n} (Y_m - Y_i) / \sum_{i=1}^{n} (c_i - c_t) , \tag{5}$$

where (c_i, Y_i) represents the i-th data point ($1 \leqq i \leqq n$), and n is the number of observed data points used in the analysis. An iterative procedure was built into the program so that only data points between c_t and c_0 are considered. As will be shown later, Eq. (5) is especially useful when methods based on Eq. (2) lead to salinity threshold values that are located to the left of the first measured data point (usually the nonsaline control). As an alternative to Eq. (5), least-squares techniques could be used to calculate s once Y_m and c_1 are known. Because least-squares methods give relatively more weight to data points that are far from the threshold value (i.e., data points associated with low yields) and because salt tolerance studies are generally more concerned with the region close to the threshold (i.e., with the higher yield values), Eq. (5) is used when NOPT = 2.

Nonlinear least-squares techniques are used whenever NOPT $\geqq$ 3. When NOPT = 3, the threshold c_t is assumed to be known beforehand and only s and Y_m are fitted to the data. When NOPT = 4, both c_t and s are calculated (Y_m is fixed), whereas for NOPT = 5 all three unknowns (Y_m, c_t and s) in Eq. (2) are determined by the program.

Salt tolerance studies on the same crop (variety) are often carried out over a period of several years. One could analyze these data on a year-to-year basis by fitting the unknown parameters to the experimental data for each year separately. Even though the maximum yield (Y_m) may vary from year to year because of varying soil, environmental or management conditions, the assumption is sometimes made that the threshold and the slope should remain constant from year to year. "Average" thresholds and/or slopes could then be derived simply by averaging the yearly values of the two parameters.

An alternative and more accurate procedure for this problem would be to fit the time-independent values of c_t and s directly to all data, while at the same time allowing Y_m to vary from year to year. This can be done when $6 \leqq$ NOPT $\leqq 10$ (see Table 1). For example, suppose that experimental data for a certain crop are available for two consecutive years. If c_t and s are assumed to remain constant for these two years, then a total of four unknown coefficients must be fitted to the data: c_t, s, and the maximum yields (Y_m^1 and Y_m^2) for the 2 years. This case is solved when NOPT = 6. The program can consider analogous problems for up to 6 years (up to eight unknown parameters). Of course, similar situations with fixed values of c_t and s and varying Y_m-values are also possible when salt tolerance studies are carried out within a fixed time period, but with different management schemes (e.g., with varying leaching fractions or irrigation methods). An example of this type is considered later.

Although Eq. (2) has been the more popular model for quantifying the salt tolerance of crops, two alternative formulations are also considered in the computer program. One expression is of the form

$$Y = Y_m/[1 + (c/c_{50})^p], \qquad (6)$$

where c_{50} is the salinity at which the yield is reduced by 50%, and p is an empirical constant. Figure 2 gives a dimensionless plot of Y_r versus c/c_{50}. Equation (6) is used in the program for NOPT-values from 11 through 17 (see Table 1). As with

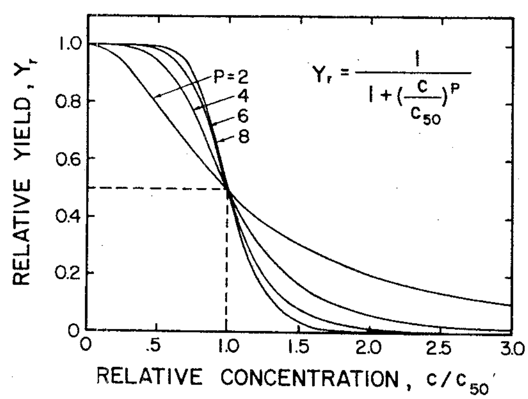

Fig. 2. Relative crop yield as a function of relative soil salinity based on Eq. (6) for several values p

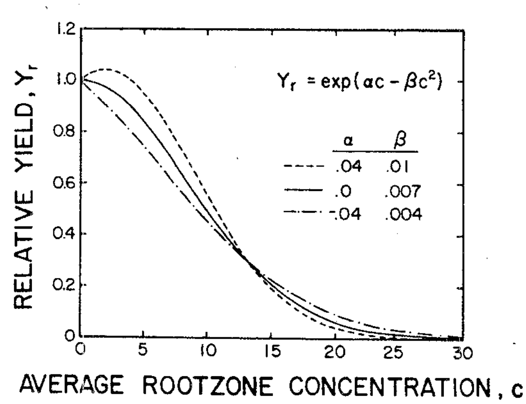

Fig. 3. Relative crop yield as a function of soil salinity based on Eq. (7) for several values of the empirical constants α and β

Eq. (2), the choice of a particular option depends on the number of unknown parameters in Eq. (6), and on the number of multiple Y_m values available for different years or treatments.

The second alternative in the computer program assumes an exponential relation between the yield and the average rootzone salinity:

$$Y = Y_m \exp(\alpha c - \beta c^2), \quad (7)$$

where α and β are empirical constants. Figure 3 shows relative salt tolerance curves based on this equation for three different combinations of α and β. Note that the curve for $\alpha > 0$ reaches a maximum at some positive value of soil salinity; this maximum is located at $c = \alpha/2\beta$. When $\alpha = 0$, the initial slope of the response function is zero, and the curve is similar in shape to the curves shown in Fig. 2. Response functions based on Eq. (7) are used whenever $18 \leq NOPT \leq 20$ (Table 1). An example of this alternative is also given.

8.1.3 Examples of Analyses

This section presents several examples illustrating the type of results that were obtained with the computer program. The examples, taken from the literature, were chosen to illustrate several of the model options. In each example, soil salinity values are the same as those used in the original publication.

8.1.3.1 Tall Fescue

This example compares two fitted curves with the experimental data from a salt tolerance trial on tall fescue (Brown and Bernstein 1953). Results for the solid line in Fig. 4 were obtained with NOPT = 5 (see Table 1), indicating that all

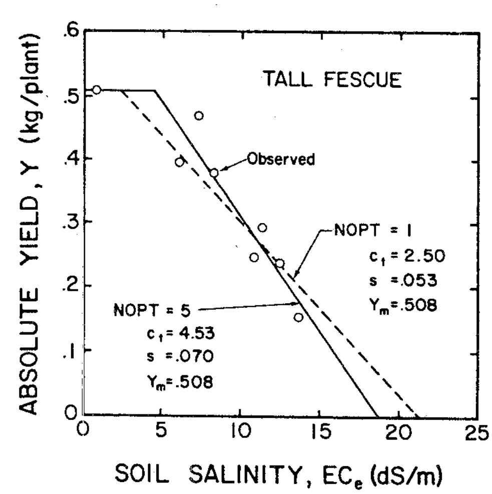

Fig. 4. Observed data and fitted salt tolerance response functions for tall fescue. (Data from Brown and Bernstein 1953)

three unknowns (c_t, s and Y_m) in Eq. (2) were fitted to the data. Note that only one point is located to the left of the threshold. This indicates that the curve could have been calculated also with NOPT = 4 by fixing Y_m equal to the maximum observed yield and carrying out a two-parameter fit for c_t and s. However, in general it is impossible to know beforehand whether or not only one data point appears to the left of c_t, and hence it is always better to calculate all three unknowns simultaneously using NOPT = 5. Because the required computer time is in the order of a few seconds or less, there is also no reason to limit the number of unknowns in the program by artificially fixing Y_m.

The dashed line in Fig. 4 is based on a linear regression fit of all data (NOPT = 1). Assuming that Y_m is equal to the control yield of the first data point, this method generated a drastically different threshold value: 2.50 for NOPT = 1 as compared to 4.53 for NOPT = 5. On the other hand, if the first data point was deleted from the data set, linear regression in this case would have generated exactly the same results as the complete three-parameter fit using NOPT = 5.

8.1.3.2 Perennial Rye

Results for the salt tolerance of perennial rye (Brown and Bernstein 1953), shown in Fig. 5, are very similar to those of the previous example. Again, only one data point appears to the left of the threshold value, indicating that NOPT = 4 and NOPT = 5 would have produced exactly the same results. Also the use of linear regression techniques would lead to the same results, again provided that the first data point is deleted from the data set.

Figure 6 shows results for the same data set when Eq. (7), rather than Eq. (2), is fitted to the data. Note that the parameter α was found to be positive, causing the curve to acquire a maximum at $c = \alpha/2\beta = 2.5$ dS m^{-1}. Judging from Figs. 5 and 6, the exponential curve failed to produce better results than the piecewise

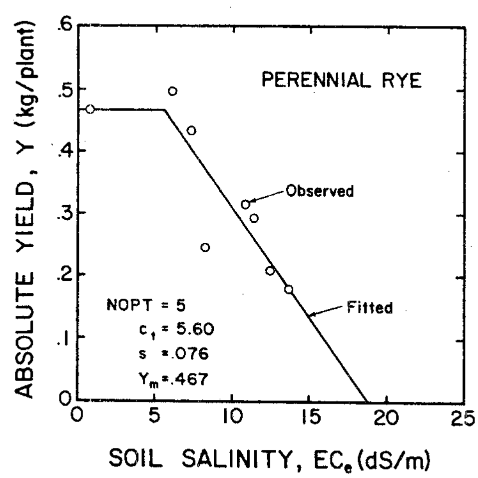

Fig. 5. Observed data and fitted salt tolerance response function for perennial rye. (Data from Brown and Bernstein 1953). The fitted curve was based on Eq. (2)

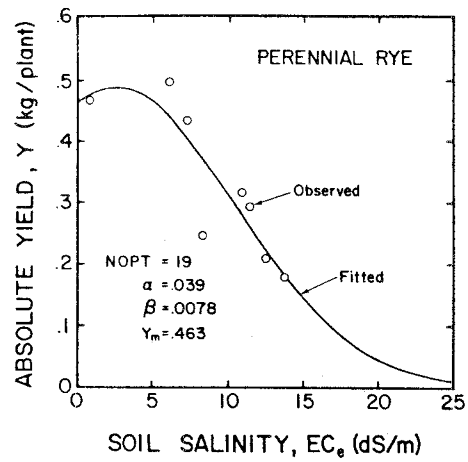

Fig. 6. Observed data and fitted salt tolerance response function for perennial rye. (Data from Brown and Bernstein 1953). The fitted curve was based on Eq. (7)

linear model. This conclusion also follows from a comparison of the sum of the squared deviations of the observed (Y_i) versus the fitted (Y_i') yield values (SSQ):

$$SSQ = \sum_{i=1}^{n} (Y_i - Y_i')^2 . \tag{8}$$

Nearly identical values for SSQ were obtained with the two models: 0.0214 for the piecewise linear model and 0.0231 for the exponential model. Therefore, both models are about equally successful in describing the salt tolerance data of perennial rye.

8.1.3.3 Tomato

Figure 7 summarizes a salt tolerance experiment for tomato (Osawa 1965). The dashed line represents the complete three-parameter fit based on Eq. (2) (NOPT = 5). Note that the threshold appears to the left of all the data points. This situation leads to a unique and well-defined value for the absolute slope. However, the fitted values for c_t and Y_m in this case are meaningless because no data points at the lower salinity values are available to fix these values. In fact, different initial estimates of the coefficients in the nonlinear least-squares procedure would lead to different fitted values for these two parameters. There are two ways of resolving this problem. One method would be to assume either that c_t is known beforehand and is equal to the salinity of the first data point on the left, or that Y_m is known and coincides with the yield at the lowest soil salinity reported. Either assumption will fix the endpoint of the dashed curve in the upper left part of Fig. 7. One can accomplish this in the program by using either NOPT = 3 (c_t is fixed) or NOPT = 4 (Y_m is fixed), respectively. Unfortunately, this method still results in either a Y_m-value that is less than the yield associated with the first data point (NOPT = 3), or a threshold salinity value that lies to the left of this point (NOPT = 4).

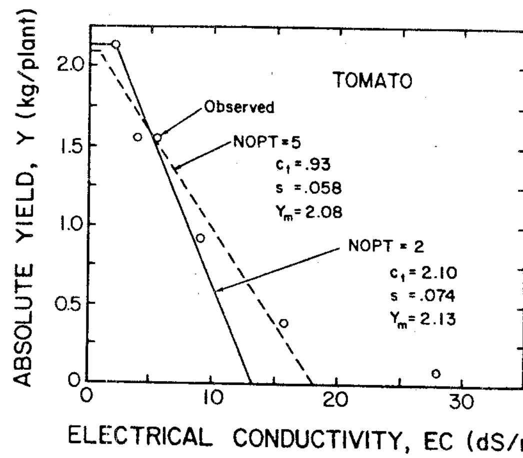

Fig. 7. Observed data and fitted salt tolerance response function for tomato. (Data from Osawa 1965)

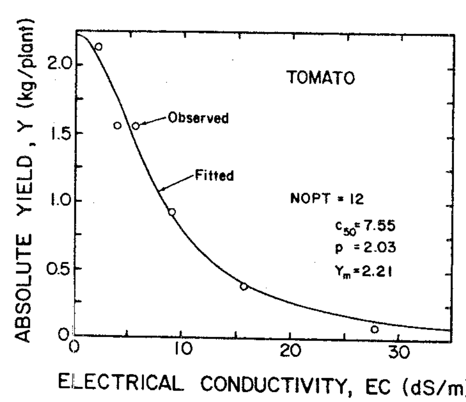

Fig. 8. Observed data and fitted salt tolerance response function for tomato. (Data from Osawa 1965). The fitted curve was based on Eq. (6)

An alternative and more realistic approach would be to fix both c_t and Y_m by their values at the first data point on the left in Fig. 7. In the program this is accomplished with a one-parameter fit for s based on Eq. (5) (NOPT = 2). Actually, the program switches automatically from NOPT = 5 to NOPT = 2 whenever all observed data points are to the right of the fitted threshold value. The solid line in Fig. 7 was obtained with NOPT = 2. Note that two data points appear to the right of c_0, the intersection between the fitted line and the concentration axis. The program uses an iterative procedure such that all points to the right of c_0 are automatically discarded from the data set. In other words, no data points are included in the analysis whenever those points produce negative yield values as calculated with the fitted curve.

For illustrative purposes, the same tomato data were also analyzed with Eq. (6). Results are presented in Fig. 8. Clearly, Eq. (6) leads to a much better fit of the data than the piecewise linear response model, especially at higher levels of salinity.

8.1.3.4 Grapefruit

In this example we analyzed the salt tolerance response function of grapefruit using the same data as listed by Feinerman et al. (1982). First the data were analyzed with NOPT = 5, i.e., for the three unknown parameters Y_m, c_t and s in Eq. (2). Figure 9 compares the fitted curve with observed data. Note that all data are located in the upper left part of the figure close to the threshold value. Because of a lack of observed data at higher soil salinities, both the threshold and the slope of the curve have extremely large standard errors. Moreover, this was the only example studied that exhibited uniqueness problems during the inversion process. Uniqueness problems become apparent when different initial estimates in the computer program generate different values for the fitted parameters. The least-squares method is based on the principle that the sum of squares (SSQ) of the deviations between the observed (Y_i) and calculated yields (Y_i') is minimized [see Eq. (8)]. In general, SSQ can be viewed as a three-dimensional function of the un-

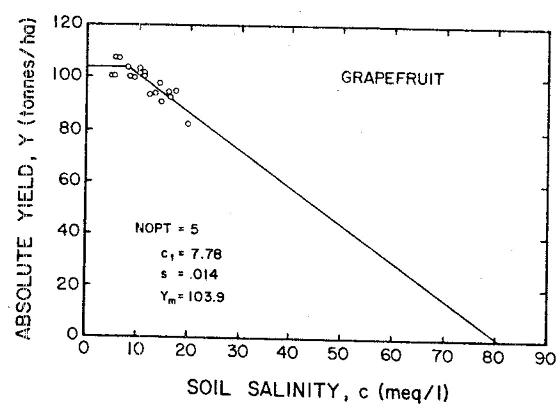

Fig. 9. Observed data and fitted salt tolerance response function for grapefruit. (Data from Feinerman et al. 1982). The fitted curve was based on Eq. (1)

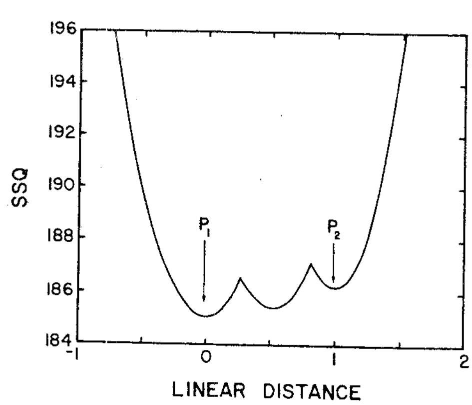

Fig. 10. Plot of SSQ evaluated along a linear line through the points P_1 and P_2 (see text for explanation)

known coefficients Y_m, c_t and s. In some cases this function may manifest multiple minima to which the least-squares method can converge. In the present example, several minima were observed, one of which was located at $P_1=(Y_m, c_t, s)_1=(103.95,\ 7.78,\ 0.0137)$, and one at $P_2=(Y_m, c_t, s)_2=(102.76,\ 9.72,\ 0.0165)$. Figure 10 graphically illustrates the variation of SSQ along a straight line through these two points. Note that along this line actually three minima with nearly identical SSQs are present. The fitted line in Fig. 9 uses the parameter values associated with the lowest SSQ (P_1 in Fig. 10). It is recommended that the least-squares inversion method be carried out with at least two different sets of initial estimates whenever the observed data are clustered around the threshold value such as in this example. If the results obtained with widely different initial estimates are identical, it is probably safe to assume that the solution is unique.

Results obtained here for grapefruit differ slightly from those obtained by Feinerman et al. (1982). This is because their regression technique differs somewhat from the nonlinear least-squares method described here. In essence, the technique used by Feinerman et al. (1982) assumes unequal variances for the two line segments on either side of the threshold salinity, while the least squares technique used here assumes that the variances for the two lines are the same. For comparison, the fitted response function of Feinerman et al. (1982) is determined by $(Y_m, c_t, s)=(102.7,\ 10.28,\ 0.0181)$, a result which is very close to point P_2 in Fig. 10.

8.1.3.5 Brome Grass

Data on the salt tolerance of brome grass were published in the form of a continuous graph by McElgunn and Lawrence (1973). To obtain a discrete set of data, points at equal intervals of soil salinity were taken from their Fig. 3. Figure 11 compares the regular three-parameter fit of Eq. (2) (NOPT = 5) with the "observed" data. Note that the data are plotted on a relative yield scale as in the original publication because no information was available on the control yield it-

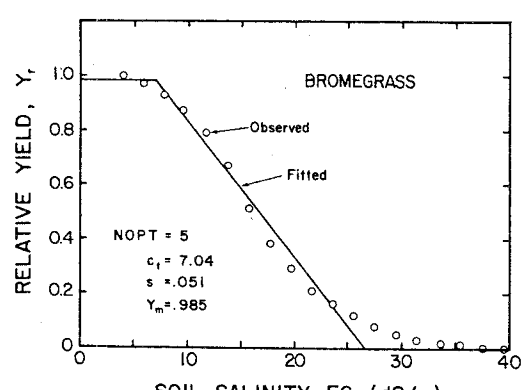

Fig. 11. Observed data and fitted salt tolerance response function for brome grass. (Data from McElgunn and Lawrence 1973). The fitted curve was based on Eq. (2)

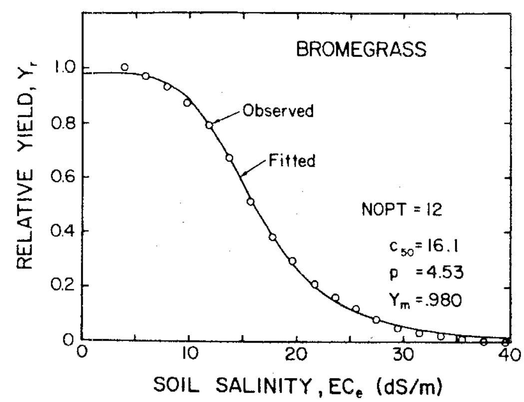

Fig. 12. Observed data and a fitted salt tolerance response function for brome grass. (Data from McElgunn and Lawrence 1973). The fitted curve was based on Eq. (6)

self. The fitted value of Y_m (0.985; see Fig. 11) was found to be slightly less than the assumed control yield, set here at exactly 1.000. The newly fitted relative yield scale hence should run between 0 and 0.985, with s being defined in terms of this new scale.

As an alternative to the three-parameter fit, the data in Fig. 11 could have been analyzed by fixing the maximum yield at 1.00 (using NOPT = 4); this implies that the control yield was determined more accurately than the other points. This would be a reasonable assumption if the control yield value was based on several replicates. No information of this kind was available, and hence there was no reason to put more weight on this control point than on any other point of the observed data set.

Because of the smooth and signoidal shape of the observed curve, the same brome grass data were also analyzed with Eq. (6). Figure 12 shows that this particular response model leads to an excellent fit of the data. A similar fit with the exponential model based on Eq. (7) was found to be somewhat less successful than the fit based on Eq. (6) (results not shown here).

8.1.3.6 Corn

Hoffman et al. (1983 a) recently performed a field experiment to establish the salt tolerance of corn grown on the organic soils of the Sacramento – San Joaquin Delta in California. The experiment was conducted over a period of three years with both sprinkler- and subsurface-irrigated treatments. The experimental data for the different years and irrigation treatments are shown in Fig. 13. The threshold salinity (c_t) and the relative slope (s) are assumed to be time-independent and also independent of the irrigation method. Thus, an 8-parameter fit based on the piecewise linear response model [Eq. (2); NOPT = 10] was determined. This approach assumes that c_t and s are constant, but that the control yield Y_m^i (i = 1.6) can vary from year to year and also as a function of the irrigation method. Figure 13 shows that the fitted curves indeed are different only with re-

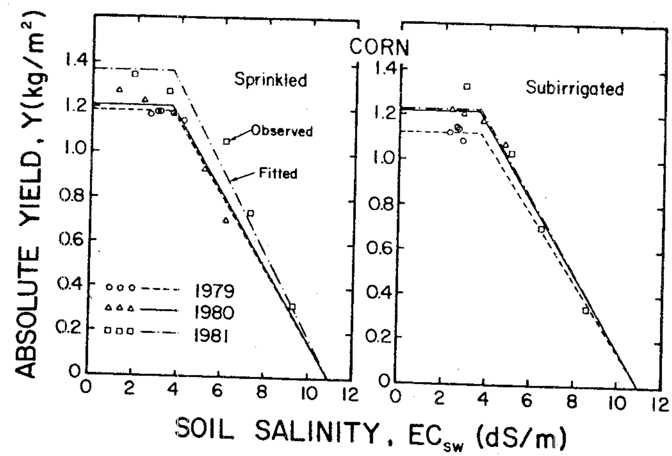

Fig. 13. Observed data and fitted salt tolerance response functions for corn. (Data from Hoffman et al. 1983a)

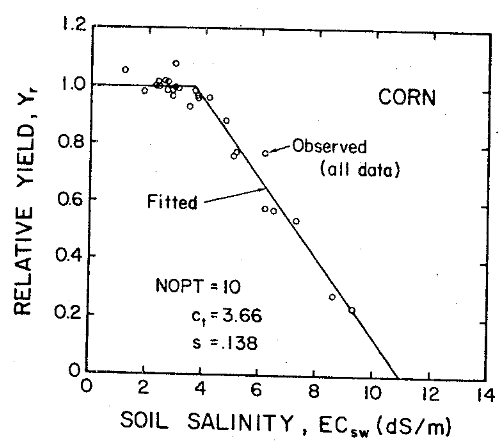

Fig. 14. Plot of the relative salt tolerance of corn as determined from the six fitted curves in Fig. 13

spect to the absolute yield. In particular, note that the values of c_1 and c_0 are identical for the six fitted curves. By dividing the absolute yields of the different treatments with the appropriate Y^i_m-value, the experimental data were normalized into relative yield fractions as shown in Fig. 14. In conclusion, the solid line in Fig. 14 expresses the relative salt tolerance of corn grown on the organic soils of the Sacramento – San Joaquin Delta from 1979 through 1981 as determined by two irrigation methods.

It is also possible to analyze the corn data by considering the two irrigation methods separately. This can be done by carrying out a 5-parameter fit (NOPT = 7; see Table 1) on both the sprinkler and the subirrigated data. Effects of the irrigation method on the fitted values of the threshold and the slope were found to be relatively small; results of this type are discussed in more detail by Hoffman et al. (1983a).

8.1.4 Summary and Conclusions

This study illustrates how salt tolerance data can be conveniently analyzed by coupling an appropriate salt tolerance model with a least-squares optimization method. Methods based on the popular piecewise linear response function and on other equally useful response functions are described. The computer program provides an efficient and accurate tool for quantifying the unknown parameters that appear in these different response functions. To allow for flexibility in analyzing different types of data sets, 20 options were included in the program. These options relate to the choice of a particular salt tolerance model, and to the type and number of unknown parameters that appear in each model. A particularly useful feature of the program is its ability to consider salt tolerance data that have been collected over a period of several years, or that pertain to different management conditions. For the linear response model this means that the salinity threshold and the relative slope are constant, while the control yield itself is allowed to vary from year to year or among different treatments.

In general, few uniqueness problems were observed when applying the nonlinear least-squares method. In one example the observed data were found to be clustered in a relatively small portion of the salinity response curve. Data of this type lead to large standard errors for the unknown coefficients. It is recommended that salt tolerance trials be carried out over a relatively broad range of salinity values with concomitant broad variations in observed crop yields. Such data provide a better definition of the response function and lead to smaller standard errors of the coefficients.

References to Chapter 8

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