Root-Zone Salinity: II. Indices for Tolerance in Agricultural Crops

H. Steppuhn,* M. Th. van Genuchten, and C. M. Grieve

ABSTRACT

This paper provides the tools for distinguishing levels of tolerance to root-zone salinity in agricultural crops. Such distinction rests on the response of a crop's product yield following the declining, sigmoid-shaped, modified compound-discount function {$Y_r = 1/[1 + (C/C_{50})^{\exp(sC_{50})}]$} for plants grown as crops exposed to increasing root-zone salinity. This nonlinear function relates relative yield (Y_r) to root-zone salinity (C) measured in equivalent saturated soil-paste extract electrical conductivity with two nonlinear parameters, the salinity level producing 50% of the nonsaline crop yield (C_{50}) and a response curve steepness constant (s) equal to the absolute value of the mean dY_r/dC from $Y_r = 0.3$ to 0.7. These discount parameters suggest the existence of a single-value salinity tolerance index (ST-Index) equal to the 50% reduction in crop yield from that of the nonsaline yield plus a tendency to maintain some product yield as the crop is subjected to salinity levels approaching C_{50}, i.e., ST-Index = $C_{50} + s(C_{50})$. The explicit purpose of this study is to determine if the discount function using biophysically relevant parameters can be applied to historical data sets. Approximations for C_{50} and s were identified in the threshold salinity (C_t) and declining slope (b) parameters of the well-known threshold-slope linear response function. Several procedures for converting C_t to C_{50} and b to s offer the linkage between these linear and nonlinear response functions. From these procedures, two regression equations, $C_{50} = 0.988[(0.5/b) + C_t] - 0.252$ and $s = 1.52b$, proved the most appropriate for the eight representative field, forage, and vegetable crops tested. The selected conversion procedures were applied to previously published C_t and b values to obtain a list of the relative root-zone salinity tolerance in agricultural crops. In addition to C_{50} and s, values for $\exp(sC_{50})$ and the ST-Index were computed for each crop. The revised list provides extension personnel and plant growth modelers the parameter values from a nonlinear analog of crop yield response to root-zone salinity.

The relative yield of an agricultural crop grown in increasingly saline rooting media has become the primary criterion with which to indicate the crop's inherent tolerance or resistance to salinity (U.S. Salinity Laboratory Staff, 1954; Ayers and Westcot, 1985; Katerji et al., 1992). If Y represents the absolute yield and Y_r the relative yield of a test crop rooted in a series of incrementally increasing saline environments,

$$Y_r = Y/Y_m \quad [1]$$

where Y_m designates the yield of the crop when grown in a root zone free of salinity (Maas and Hoffman, 1977; Maas, 1990). Averaged spatially and temporally, the salinity (C) of the subsurface interstitial solutions can be measured in solute concentration, osmotic potential, or electrical conductivity. As detailed in the companion paper, Steppuhn et al. (2005) showed that the modified compound-discount function,

$$Y_r = 1/[1 + (C/C_{50})^{\exp(sC_{50})}] \quad [2]$$

resulted in the lowest root mean square error among the six functions tested. Equation [2] describes a function with two biophysically based parameters: C_{50}, the salinity (C) at $Y_r = 0.5$, and s (a steepness parameter) identified as an approximate estimate of the absolute value of the mean dY_r/dC for the equation from Y_r = 0.3 to 0.7.

If the term p is substituted for $[\exp(sC_{50})]$ in Eq. [2], a form of the modified discount function results, which was introduced by van Genuchten (1983) and van Genuchten and Hoffman (1984) and used by van Genuchten and Gupta (1993) and Steppuhn et al. (1996):

$$Y_r = 1/[1 + (C/C_{50})^p] \quad [3]$$

where p is shape parameter with no biophysical characteristic.

If C_{50} and s are combined such that the salinity level associated with a 50% yield reduction (C_{50}) plus a measure of the tendency to maintain some product yield as the crop is subjected to increasing salinity levels approaching C_{50}, a comparative, single-value, salinity tolerance index (ST-Index) is defined:

$$\text{ST-Index} = C_{50} + sC_{50} \quad [4]$$

The ST-Index is proposed as an indicator of the inherent salinity tolerance or resistance of agricultural crops to root-zone salinity.

Since 1978, almost all crop salt-tolerance lists in the literature follow the first and second line segments of the three-piece linear response function. This function was proposed by Maas and Hoffman (1977) as the threshold-slope model and functionalized by van Genuchten (1983):

$$\begin{aligned} Y_r &= 1 & 0 < C < C_t \\ Y_r &= 1 - b(C - C_t) & C_t < C < C_0 \\ Y_r &= 0 & C > C_0 \end{aligned} \quad [5]$$

where b is the absolute value of the declining slope in Y_r with C, C_t is the maximum value of salinity without a yield reduction (the threshold C), and C_0 is the lowest value of C where $Y_r = 0$. The two-piece, threshold-slope response function (the first and second linear segments)

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Abbreviations: EC_e, electrical conductivity of saturated soil paste extract; EC_i, electrical conductivity of the irrigated water; EC_s, electrical conductivity of test solution; FAO, Food and Agriculture Organization, United Nations; ST-Index, salinity tolerance index.

Table 1. Selected-line-segments procedure for converting the linear parameters of C_t and b to the discount parameters of C_{50} and s by selecting points from the horizontal and declining straight lines of the threshold-slope function, where $C = EC_e$ in dS m^{-1}.

Step	Procedure
1	Solve the middle equation of the three-piece linear model $[Y_r = 1 - b(C_{0.5} - C_t)]$ for $C_{0.5}$, the mid-point of the declining slope, where $Y_r = 0.5$, i.e., $C_{0.5} = C_t + (0.5/b)$
2	Select additional C-points from the threshold-slope lines: ± 0.5 dS m^{-1}, ± 1 dS m^{-1}, ± 2 dS m^{-1}, etc. of $C_{0.5}$ from the declining line, and C = 1, 2, and 3 dS m^{-1} from the horizontal line
3	Using the linear threshold-slope model, calculate relative yields (Y_{rlin}) for the 10 or more selected points
4	Regress Y_{rlin} with C by the modified discount function $\{Y_r = 1/[1 + (C/C_{50})^{\exp(sC50)}]\}$ to determine Y_{rm} as a regression parameter; generally, this Y_{rm}–value will deviate from 1.0
5	Subtract 1.00 from Y_{rm} to determine the Y_r offset
6	Rescale the linear relative yields (Y_{rlin}) into nonlinear relative sigmoid yields (Y_{rs}) with the Y_r offset applied to all Y_{rlin} values for the selected C points
7	Regress the sigmoidal Y_{rs} with C by the modified discount function $\{Y_r = 1/[1 + (C/C_{50})^{\exp(sC50)}]\}$ to determine C_{50} and s as regression parameters
8	Using $p = \exp(sC_{50})$, calculate p

has served as an approximation of the modified discount function. Its parameters C_t and b provided the basis for salinity tolerance lists for 25 yr. The one exception is a list presented by van Genuchten and Gupta (1993) based on the discount model of Eq. [3]. Their list relies on two different regression parameters (C_{50} and p) to index the salt-tolerance relationship between degree of salinity and relative crop yield.

In our companion paper (Steppuhn et al., 2005), we submitted the argument that the product yields of agricultural crops relate more closely to the modified discount function rather than to the threshold slope model. Unfortunately, only limited data are available for the calculation of C_{50}, s, the ST-Index, and for the generation of an associated crop salt-tolerance list. Thus, the objectives of this study were to evaluate different methods for converting the respective linear threshold-slope parameters of C_t and b to C_{50} and s of the nonlinear modified discount function and to apply the most appropriate of these conversions to a current threshold-slope crop list for salinity tolerance. Besides conversion to the nonlinear parameters of C_{50} and s, the selected methods would serve to calculate p and the ST-Index, which, in turn, were used to generate a revised list of the relative salinity tolerances in agricultural crops.

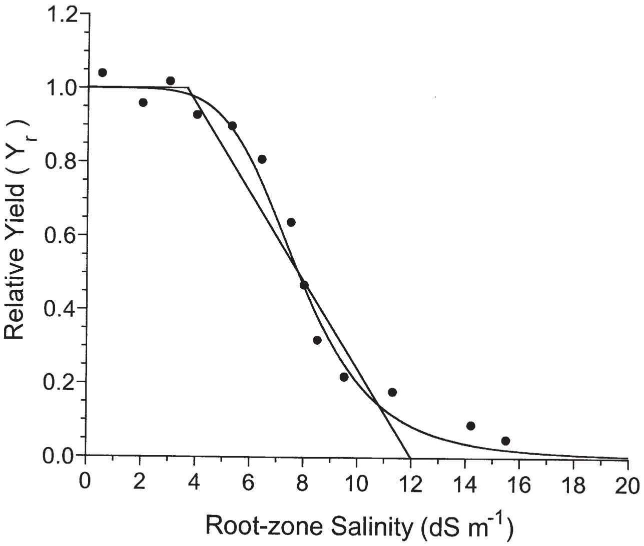

Fig. 1. Typical crop yield response to increasing root-zone salinity described by the modified discount and the threshold-slope functions.

CONVERSION METHODS

If the linear, threshold-slope response model of crop yield with increasing root-zone salinity serves as an approximation of the nonlinear modified-discount response function, it should be possible to evaluate the parameters of the nonlinear function from relationships on the basis of the linear approximation. In other words, if C_t and b are known for any crop, this information can be used to estimate C_{50}, s, and p for the crop. In this paper, we evaluate several methods for converting C_t and b to C_{50} and s: (i) a direct method, (ii) an analytical method, and (iii) several empirical methods.

Direct Conversion

The most general method of determining C_{50} and s from C_t and b follows a selected-line-segment procedure (Table 1). In this method, selected pairs of relative yield and root-zone salinity are calculated from the two linear segments of the threshold-slope model and used in nonlinear regressions to fit a least-squares discount curve giving the parameter estimates of C_{50} and s. The merits of this method are that both nonlinear parameters are determined together and that the method universally applies to all salt-tolerance response data which have been or will be analyzed with the threshold-slope function.

Analytical Conversion

Typically, the response data of relative crop yield with increasing root-zone salinity vary. A nonlinear statistical fit of the modified discount response function to such data by appropriate software, e.g., JMP (SAS, 1995), results in estimates of C_{50} and s and in a fitted plot of the function (Fig. 1). A threshold-slope analysis of the same data also provides a fitted functional plot but with parameters C_t and b (Fig. 1). These plots reveal (i) that the functions each relate to the same data, (ii) that the inflection point of the discount curve likely falls on or close to the threshold-slope line, (iii) that $s > b$ (i.e., the value of s from the discount curve is greater than the absolute value of the slope b of the threshold-slope model), (iv) that the salinity levels for C_{mid} and C_{50} (where Y_r equals half of the salinity-free relative yields of their respective linear and the nonlinear response functions) are very nearly equal, and (v) that, as indicated by van Genuchten and Hoffman (1984), Maas (1990), and Maas and Grattan (1999), the discount plot more precisely describes the response data.

Our analytical and some of our empirical conversions are based on analyses of midpoints of the discount and the threshold-slope response models. The slope of the Eq. [3] discount curve is given by its first derivative:

$$(dY_r/dC) = -[1 + (C/C_{50})^p]^{-2}\,(C/C_{50})^{p-1}\,(p/C_{50}) \quad [6]$$

If, for any value of C, the absolute value of the first derivative is set equal to the steepness parameter s, then,

$$s = |dY_r/dC|.$$

From Eq. [6],
$$s = [1 + (C/C_{50})^p]^{-2}\,(C/C_{50})^{p-1}\,(p/C_{50}) \quad [7]$$

or
$$p = (sC_{50})\,[1 + (C/C_{50})^p]^2\,(C/C_{50})^{1-p} \quad [8]$$

At the inflection point of the discount function, the second derivative of Eq. [3] is equal to zero:

$$dY_r^2/dC^2 = ds/dC = 0 \quad [9]$$

which simplifies to
$$(C/C_{50}) = [(p - 1)/(p + 1)]^{1/p} \quad [10]$$

Substitution of Eq. [10] into Eq. [8] and simplification leads to

$$sC_{50} = [(p^2 - 1)/4p]\,[(p + 1)/(p - 1)]^{1/p} \quad [11]$$

which, as will be shown later, provides one method of quasi-empirical regression between s and b.

Empirical Conversion

Over the years, scientists at the U.S. Salinity Laboratory have collected the results from a large number of salt tolerance response tests conducted worldwide (Francois and Maas, 1978, 1985; Ulery et al., 1998). These data sets formed the basis for response-function studies by Maas and Hoffman (1977), van Genuchten and Hoffman (1984), and van Genuchten and Gupta (1993).

In the latter study, this database was divided into four groups: field, forage, vegetable, and fruit-tree crops. Most fruit-tree data sets were discarded because of generally too few or unreliable experimental data. Of the remaining data sets, some were also judged to be unsuitable because of insufficient or unreliable data. Typically, the unused data contained as few as three data pairs, exhibited severe scattering in the data points, or clustered heavily within only one part of the response function. The remaining salt tolerance database consisted of experiments involving 45 field crops, 62 forage crops, and 57 vegetable and fruit crops, giving a total of 164 data sets. These formed the core data utilized in this study from which the values for C_t, b, C_{50}, s, and p were obtained either from the original reports of the experiments or from analyses of the original data.

Converting C_t to C_{50}

To ascertain if C_{50} could reliably be determined from C_t empirically, values of the two parameters obtained from the core data sets were linearly regressed (SAS, 1995). The threshold salinity (C_t) explained some 77% of the variation analyzed in the C_{50} data within a root mean square error (RMS error) of ± 2.3 dS m^{-1} (Fig. 2).

Another approach involved the middle segment of the threshold-slope function. Solving this segment of Eq. [5] for C gave

$$C = [(1 - Y_r)/b] + C_t \quad [12]$$

At $C = C_{\mathrm{mid}}$,
$$Y_r = 0.5 \quad [13]$$

and, hence,
$$C_{\mathrm{mid}} = (0.5/b) + C_t \quad [14]$$

From Fig. 1, C_{50} would seem to be empirically related to C_{mid}, especially if the inflection point of the discount curve falls on or close to the threshold-slope line. Consequently, a linear regression of C_{50} as a function of C_{mid} was conducted with values from the core data sets (Fig. 3). The resulting coefficient of determination (R^2) and RMS error equaled 0.98 and ± 0.53 dS m^{-1}, respectively. The statistical relationship from this regression,

$$C_{50} = 0.988C_{\mathrm{mid}} - 0.252 \quad [15]$$

indicated that both the slope and the intercept were statistically significant ($p_\alpha \leq 0.01$) and that C_{50} very nearly equaled C_{mid}.

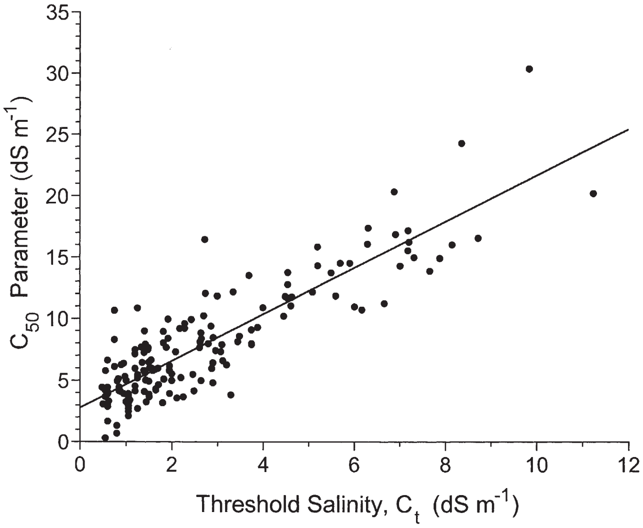

Fig. 2. The modified discount C_{50} parameter derived from a regression with the threshold salinity (C_t) of the threshold-slope linear model for the core data sets. ($C_{50} = 2.786 + 1.891C_t$) ($R^2 = 0.77$, RMS error = ± 2.3 dS m^{-1})

Converting b to s

A linear regression to establish a direct relationship of s as a function of b using the core data sets resulted in a R^2 value of 0.746 with the RMS error = ± 0.058 (dS m^{-1})$^{-1}$ (Fig. 4):

$$s = 1.523b - 0.0015 \quad [16]$$

wherein the intercept was not statistically different from zero. However, s can also be calculated from p by Eq. [11]. But, a linear regression of p as a fit of b using the same data correlated with R^2 equal to only 0.164 (data not shown).

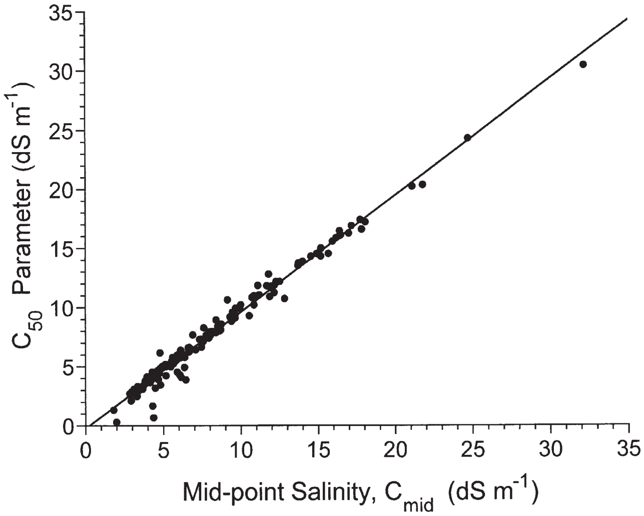

Fig. 3. The modified discount C_{50} parameter derived from a regression with the salinity (C_{mid}) at 0.5 of the relative yield (Y_r) in the threshold-slope linear model for the core data sets. ($C_{50} = -0.252 + 0.988C_{\mathrm{mid}}$) ($R^2 = 0.98$, RMS error = ± 0.53 dS m^{-1})

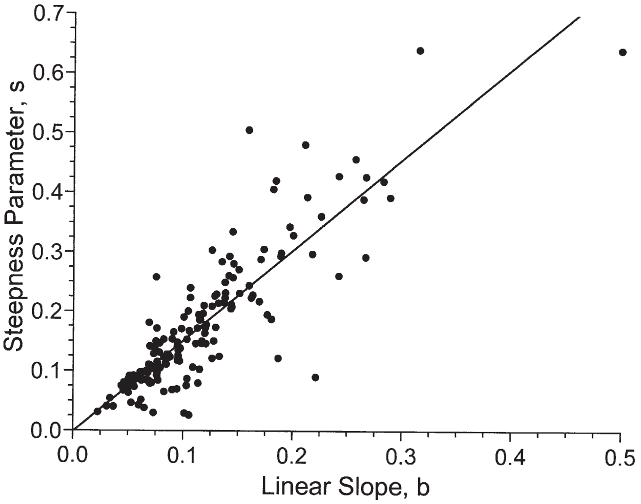

Fig. 4. The steepness parameter (s) of the modified discount function derived from a regression with the slope (b) of the three-piece linear model for the core data sets. ($s = 1.523b$) [$R^2 = 0.746$, RMS error = ± 0.058 (dS m^{-1})$^{-1}$]

If, for convenience, the right side of Eq. [11] is expressed as Fn(p), and moved to the left side, and s is replaced by 1.52b of Eq. [16],

$$\mathrm{Fn}(p) = 1.52bC_{50} \qquad [17]$$

Further, if the expression for C_{50} in Eq. [15] is substituted into Eq. [17] and consolidated,

$$\mathrm{Fn(p)} = 1.50bC_{\mathrm{mid}} - 0.383\mathrm{b} \qquad [18]$$

Next, if C_{mid} of Eq. [14] is substituted into Eq. [18]:

$$\mathrm{Fn}(p) = b(1.50C_{\mathrm{t}} - 0.383) + 0.75 \qquad [19]$$

Equation [19] suggests that a regression of

$$\mathrm{Fn}(p) = \mathrm{Function}(bC_{\mathrm{t}}) \qquad [20]$$

using the core data set could provide an empirical link between p and b. An exponential transformation leads to two other possible regression relationships,

$$\mathrm{Fn}(p) = \mathrm{Function}[\exp(bC_{\mathrm{t}})] \qquad [21]$$

$$\ln[\mathrm{Fn}(p)] = \mathrm{Function}(bC_{\mathrm{t}}) \qquad [22]$$

In addition, Eq. [20] and the relationship, $p = \exp(sC_{50})$, from Eq. [2] and [3] suggest that three more possible regression fits of p or ln(p) by (bC_{t}) might serve as candidates for converting b to p and then to s:

$$\ln(p) = \mathrm{Function}(bC_{\mathrm{t}}) \qquad [23]$$

$$p = \mathrm{Function}[\exp(bC_{\mathrm{t}})] \qquad [24]$$

$$p = \mathrm{Function}(bC_{\mathrm{t}}) \qquad [25]$$

Table 2. Coefficient of determination (R^2) and root mean square error (RMS error) for six empirical relationships for converting linear slope (b) and threshold salinity (C_{t}) parameters to the discount p parameter from the core data set.

			RMS error	
Relationship†	**R^2**	**N‡**	**Fn(p)**	**p**
$\mathrm{Fn}(p) = \exp(bC_{\mathrm{t}})$	0.60	158	0.147	
$\mathrm{Fn}(p) = (bC_{\mathrm{t}})$	0.58	158	0.151	
$\ln[\mathrm{Fn}(p)] = (bC_{\mathrm{t}})$	0.57	158	0.157	
$p = \exp(bC_{\mathrm{t}})$	0.55	161		0.763
$p = (bC_{\mathrm{t}})$	0.54	161		0.771
$\ln(p) = (bC_{\mathrm{t}})$	0.48	158		0.771

† p = prevention parameter, b = slope of the relative yield with salinity relationship, C_{t} = threshold salinity, Fn(p) = function of p derived from the second derivative of the discount response equation set equal to zero and simplified: $\mathrm{Fn}(p) = [(p^2 - 1)/4p]\,[(p + 1)/(p - 1)]^{1/p}$.
‡ N = number of data pairs [$\ln(p) > 0.0$; $1.0 < p < 10.0$].

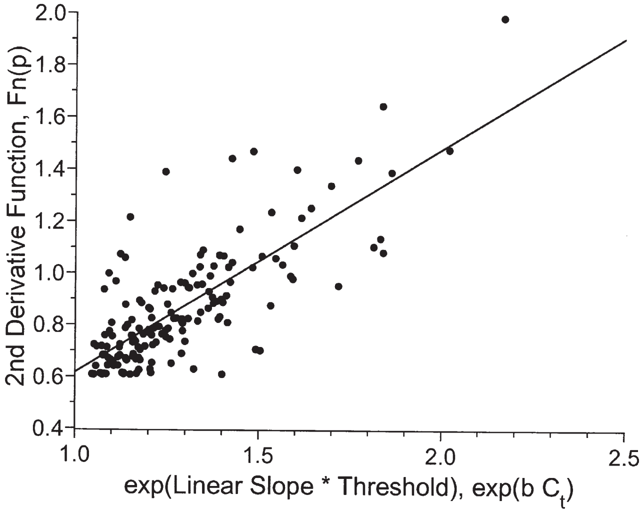

Fig. 5. Regression of the function Fn(p) derived from the second derivative of the discount equation set to zero with the exponential of the product of the linear threshold-slope parameters, slope (b), and threshold salinity (C_{t}), for the core data sets. {$\mathrm{Fn}(p) = [(p^2 - 1)/4p]\,[(p + 1)/(p - 1)]^{1/p} = -0.245 + 0.862\,[\exp(bC_{\mathrm{t}})]$} ($R^2 = 0.60$, RMS error = ± 0.147)

The six regressions (Eq. [20] through [25]) were conducted with a variable number of core data sets automatically entering each regression depending on the number of sets that contained a value of p within the range of $1 < p < 10$. As outlined in Table 2, comparisons of the statistics from the six regressions with bC_{t} for converting b to p favor Eq. [21], and is plotted in Fig. 5. Once Fn(p) was determined, we used a simple linear regression ($R^2 = 0.988$, $2.5 < p < 10.0$),

$$\mathrm{Fn}(p) = 0.10601 + 0.24075p \qquad [26]$$

to determine p from Fn(p) and the relationship, $s = \ln(p)/\mathrm{C}_{50}$, to obtain s.

Selecting Conversion Methods

Relative crop yields measured in eight salt-tolerance response experiments were used to compare the precision associated with parameter-conversion methods (Table 3). The methods for converting C_{t} and b to C_{50} and s were applied to the measured data from three field, three forage, and two vegetable experiments with eight different crops. The data were reported in four experiments taken from within the core data sets and four from separate sets. The test experiments provided values for the threshold salinity (C_{t}), linear slope (b), and mid-point salinity (C_{mid}) used in the comparisons (Table 3). Nonlinear discount regressions with the actual experimental response data resulted in best-fit values for C_{50} and s for each test experiment against which the conversion methods were compared. The methods used to convert the linear parameters of the eight crop responses (experiments) included the empirical conversions based on the respective $y \times x$ regression fits of $C_{50} \times (C_{\mathrm{t}})$ and $C_{50} \times (C_{\mathrm{mid}})$ shown in Fig. 2 and 3, $s \times (b)$ in Fig. 4, and $\mathrm{Fn}(p) \times \exp(bC_{\mathrm{t}})$ with $s = \ln(p)/C_{50}$ in Fig. 5. The selected-line-segments procedure from Table 1 provided the third conversion method for both C_{50} and s.

Table 3. Threshold salinity (C_t) and slope (b) determined by the three-piece linear model relating relative yield (Y_r) to salinity (C), and salinity (C_{mid}) at $0.5Y_r$ for three field, three forage, and two vegetable crops on the basis of reported tests.†

Crop	C_t	b	C_{mid}	Reference
	dS m^{-1}	(dS m^{-1})$^{-1}$	dS m^{-1}	
Rye (grain)	9.40	0.0726	16.29	Francois et al., 1989
Sorghum (grain)	6.80	0.1590	9.95	Francois et al., 1984
Wheat	2.88	0.1514	6.18	USSL, 1979
Harding grass	4.62	0.0763	11.17	Brown and Bernstein, 1953
Perennial Ryegrass	5.60	0.0762	12.16	Brown and Bernstein, 1953
Alfalfa	1.25	0.0751	7.91	Brown and Hayward, 1956
Carrot	1.01	0.1710	3.94	Magistad et al., 1943; Osawa, 1965
Turnip	0.75	0.0885	6.40	Francois, 1984

† USSL = Unpublished U.S. Salinity Laboratory data.

Table 4. Eight crop comparisons of the discount C_{50} parameter computed by three conversion methods [selected-line-segments, linear threshold (C_t), and linear mid-salinity (C_{mid})] with percent difference from the C_{50} derived from actual data points in parentheses.

	C_{50}			
Crop and data source	Actual data points	Selected line segments	C_{50} = (C_t)	C_{50} = (C_{mid})
	dS m^{-1}	dS m^{-1} (% of actual)		
Rye (grain)	16.40	17.41 (6.13)	20.56 (25.33)	15.836 (−3.46)
Francois et al., 1989	N = 12	N = 12		
Sorghum (grain)	10.18	9.90 (−2.70)	15.65 (53.78)	9.58 (−5.88)
Francois et al., 1984	N = 12	N = 11		
Wheat	5.98	6.09 (1.88)	8.22 (37.50)	5.85 (−2.18)
USSL, 1979	N = 8	N = 11		
Harding grass	11.05	10.88 (−1.55)	11.52 (4.21)	10.78 (−2.44)
Brown and Bernstein, 1953	N = 8	N = 11		
Perennial ryegrass	11.97	12.09 (1.05)	13.38 (11.89)	11.76 (−1.69)
Brown and Bernstein, 1953	N = 8	N = 10		
Alfalfa	7.66	7.68 (0.33)	5.14 (−32.85)	7.56 (−1.30)
Brown and Hayward, 1956	N = 12	N = 11		
Carrot	4.04	4.42 (9.41)	4.70 (16.35)	3.64 (−9.90)
Magistad, 1943 and Osawa, 1965	N = 12	N = 12		
Turnip	5.97	6.51 (8.93)	4.49 (−24.84)	6.13 (1.71)
Francois, 1984	N = 4	N = 12		

Table 5. Eight crop comparisons of the discount steepness parameter s computed by three conversion methods [selected-line-segments, $s \times \mathrm{Fn}(p)$, and $s \times (b)$] with percent difference from the s derived from actual data points in parentheses.

	s			
Crop and data source	Actual data points	Selected line segments	$s \times \mathrm{Fn}(p)$†	$s \times (b)$
	(dS m^{-1})$^{-1}$	(dS m^{-1})$^{-1}$ (% of actual)		
Rye (grain)	0.1072	0.0891 (−16.87)	0.1054 (−1.67)	0.1105 (3.16)
Francois et al., 1989	N = 12	N = 12		
Sorghum (grain)	0.2202	0.1971 (−10.48)	0.2175 (−1.23)	0.2417 (9.77)
Francois et al., 1984	N = 12	N = 11		
Wheat	0.2308	0.2290 (−0.79)	0.2341 (1.44)	0.2306 (−0.08)
USSL, 1979‡	N = 8	N = 11		
Harding grass	0.1151	0.1142 (−0.78)	0.1161 (−0.83)	0.1162 (0.96)
Brown and Bernstein, 1953	N = 8	N = 11		
Perennial ryegrass	0.1114	0.1096 (−1.66)	0.1160 (4.14)	0.1161 (4.17)
Brown and Bernstein, 1953	N = 8	N = 10		
Alfalfa	0.1128	0.1154 (2.27)	0.1157 (2.61)	0.1143 (1.36)
Brown and Hayward, 1956	N = 12	N = 11		
Carrot	0.2592	0.2173 (−16.17)	0.2510 (−3.17)	0.2604 (0.46)
Magistad, 1943 and Osawa, 1965	N = 12	N = 12		
Turnip	0.1251	0.1142 (−8.71)	0.1422 (13.65)	0.1348 (7.75)
Francois, 1984	N = 4	N = 12		

† Regression fit of $\mathrm{Fn}(p) \times [\exp(bC_t)]$ and $s = \ln(p)/C_{50}$

‡ STTL, unpublished data, U.S. Salinity Laboratory.

RESULTS AND APPLICATION OF CONVERSIONS

Given the inherent variability associated with product yields from crops grown in environments with increasing root-zone salinity, the errors in parameter conversions from linear to nonlinear response functions could not reasonably be expected to fall much less than ±10% of the actual values. The direct regression method [C_{50} fit × (C_t)] for converting C_t to C_{50} using the two parameters failed to achieve the ± 10% error level in seven out of eight test experiments (Table 4). Both the selected-line-segments and the fitted C_{50} × (C_{mid}) methods realized C_{50} values for all eight test experiments falling within the 10% error limit. In five out of the eight experiments, the C_{50} error stayed within a limit of ±5% in the selected-line-segment method and six out of eight in the C_{50} fit × (C_{mid}) method.

In comparing methods for converting b to s, the

Table 6. Salinity tolerance of agricultural crops.†

Crop			Nonlinear tolerance parameter				
Common name	**Botanical name‡**	**Tolerance§ based on**	**C_{50} (EC$_e$) dS/m**	**p Shape**	**s Steepness**	**Salinity tolerance index**	**References**
			Fiber, grain, and special crops				
Artichoke, Jerusalem	*Helianthus tuberosus* L.	Tuber yield	5.29	2.17	0.146	6.06	Newton et al., 1991
Barley¶ (irrigated)	*Hordeum vulgare* L.	Grain yield	17.53	3.80	0.076	18.87	Ayers et al., 1952; Hassan et al., 1970a
Barley# (dryland)	*Hordeum vulgare* L.	Grain yield	7.51	2.18	0.104	8.29	Steppuhn, 1993
Canola or rapeseed	*Brassica campestris* L. [syn. *B. rapa L.*]	Seed yield	12.86	12.46††	0.213	15.60	Francois, 1994a
Canola or rapeseed	*B. napus* L.	Seed yield	14.42	13.50††	0.198	17.27	Francois, 1994a
Canola# (dryland)	*B. napus* L.	Seed yield	7.10	2.46	0.126	8.00	Steppuhn et al., 2002
Corn‡‡	*Zea mays* L.	Ear FW	5.54	2.75	0.183	6.56	Bernstein and Ayers, 1949b (p. 41–42); Kaddah and Ghowail, 1964
Cotton	*Gossypium hirsutum* L.	Seed cotton yield	16.86	3.80	0.079	18.19	Bernstein, 1955 (p. 37–41), 1956 (p. 33–34); Bernstein and Ford, 1959a
Crambe	*Crambe abyssinica* Hochst. ex R. E. Fries	Seed yield	9.32	2.52	0.099	10.25	Francois and Kleiman, 1990
Flax	*Linum usitatissimum* L.	Seed yield	5.54	2.75	0.183	6.56	Hayward and Spurr, 1944
Guar	*Cyamopsis tetragonoloba* (L.) Taub.	Seed yield	11.35	18.88	0.259	14.29	Francois et al., 1990
Kenaf	*Hibiscus cannabinus* L.	Stem DW	12.01	8.35	0.177	14.13	Francois et al., 1992
Peanut	*Arachis hypogaea* L.	Seed yield	4.61	7.67	0.442	6.65	Shalhevet et al., 1969
Rice, paddy§§	*Oryza sativa* L.	Grain yield	6.83	3.48	0.183	8.08	Ehrler, 1960; Narale et al., 1969; Pearson, 1959; Venkateswarlu et al., 1972
Rye	*Secale cereale* L.	Grain yield	15.84	5.76	0.111	17.59	Francois et al., 1989
Sorghum	*Sorghum bicolor* (L.) Moench	Grain yield	9.57	10.16	0.242	11.89	Francois et al., 1984
Soybean	*Glycine max* (L.) Merrill	Seed yield	7.16	8.85	0.305	9.34	Abel and MacKenzie, 1964; Bernstein et al., 1955 (p. 35–36); Bernstein and Ogata, 1966
Sugar beet¶¶	*Beta vulgaris* L.	Storage root	15.04	3.86	0.090	16.39	Bower et al., 1954
Sugarcane	*Saccharum officinarum* L.	Short DW	9.80	2.41	0.090	10.68	Bernstein et al., 1966; Dev and Bajwa, 1972; Syed and El-Swaify, 1972
Sunflower	*Helianthus annuus* L.	Seed yield	14.37	2.99	0.076	15.46	Cheng, 1983; Francois, 1996
Triticale	× *Triticosecale* Wittmack	Grain yield	25.53	2.64	0.038	26.51	Francois et al., 1988
Wheat, leavened bread (irrigated)	*Triticum aestivum* L.	Grain yield	12.63	3.92	0.108	14.00	Asana and Kale, 1965; Ayers et al., 1952; Hayward and Uhvits, 1944
Wheat, leavened bread (irrigated)	*Triticum aestivum* L.	Grain yield	5.85	3.85	0.242	7.89	USSL, 1979
Wheat, leavened bread# (dryland)	*Triticum aestivum* L.	Grain yield	2.76	1.67	0.186	3.27	Steppuhn and Wall, 1997
Wheat, flat bread# (dryland)	*Triticum aestivum* L.	Grain yield	2.97	2.25	0.273	3.78	Steppuhn and Wall, 1997
Wheat, pastry#	*Triticum aestivum* L.	Grain yield	6.06	3.65	0.214	7.35	Steppuhn and Wall, 1997
Wheat (semidwarf)## (irrigated)	*Triticum aestivum* L.	Grain yield	24.71	3.09	0.046	25.84	Francois et al., 1986
Wheat, Durum (irrigated)	*T. turgidum* L. var. *durum* Desf.	Grain yield	18.58	2.93	0.058	19.65	Francois et al., 1986
Wheat, Durum# (dryland)	*T. turgidum* L. var. *durum* Desf.	Grain yield	5.36	3.67	0.243	6.66	Steppuhn and Wall, 1997
			Grasses and forage crops				
Alfalfa	*Medicago sativa* L.	Shoot DW	8.49	2.57	0.111	9.43	Bernstein and Francois, 1973; Bernstein and Ogata, 1966, Bower et al., 1969; Brown and Hayward, 1956; Gauch and Magistad, 1943; Hoffman et al., 1975
Alfalfa#	*Medicago sativa* L.	Shoot DW	6.20	1.80	0.095	6.79	Steppuhn et al., 1999
Barley (forage) ¶	*Hordeum vulgare* L.	Shoot DW	12.63	3.92	0.108	14.00	Dregne, 1962; Hassan et al., 1970a
Bermudagrass†††	*Cynodon dactylon* L. Pers.	Shoot DW	14.28	4.02	0.097	15.68	Bernstein and Ford, 1959b (p. 39–44); Bernstein and Francois, 1962 (p. 37–38); Langdale and Thomas, 1971
Bromegrass, smooth	*Bromus inermis* Leyss.	Shoot DW	16.10	4.53	0.094	17.61	McElgunn and Lawrence, 1973
Broadbean	*Vicia faga* L.	Shoot DW	6.47	2.58	0.146	7.42	Ayers and Eberhard, 1960
Clover, alsike	*Trifolium hybridum* L.	Shoot DW	5.35	2.66	0.183	6.32	Ayers, 1948a
Clover, Berseem	*T. alexandrinum* L.	Shoot DW	9.90	2.36	0.087	10.76	Asghar et al., 1962; Ayers and Eberhard, 1958 (p. 36–37); Ravikovitch and Porath, 1967; Ravikovitch and Yoles, 1971
Clover, ladino	*Trifolium repens* L.	Shoot DW	5.35	2.66	0.183	6.32	Ayers, 1948b; Gauch and Magistad, 1943
Clover, red	*T. pratense* L.	Shoot DW	5.35	2.66	0.183	6.32	Ayers, 1948b; Saini, 1972

Continued next page.

Table 6. Continued.

Crop		Tolerance§ based on	Nonlinear tolerance parameter				References
Common name	Botanical name‡		C_{50} (EC$_e$) dS/m	p Shape	*s* Steepness	Salinity tolerance index	
Clover, strawberry	*T. fragiferum* L.	Shoot DW	5.35	2.66	0.183	6.32	Ayers, 1948b; Bernstein and Ford, 1959b (p. 39–44); Gauch and Magistad, 1943
Corn (forage)‡‡	*Zea mays* L.	Shoot DW	8.20	2.52	0.113	9.13	Hassan et al., 1970b; Ravikovitch, 1973; Ravikovitch and Porath, 1967
Cowpea (forage)	*Vigna unguiculata* (L.) Walp.	Shoot DW	6.71	3.08	0.168	7.83	West and Francois, 1982
Fescue, tall	*Festuca elatior* L.	Shoot DW	12.92	2.84	0.081	13.96	Bower et al., 1970; Brown and Bernstein, 1953 (p. 44–46)
Fescue, tall# (dryland)	*Festuca arundinacea* Schreber	Shoot DW	7.97	1.94	0.083	8.63	Steppuhn, 1997
Foxtail, meadow	*Alopecurus pratensis* L.	Shoot DW	6.38	2.54	0.146	7.31	Brown and Bernstein, 1953 (p. 44–46)
Hardinggrass	*Phalaris tuberosa* L. var. *Stenoptera* (Hack) A.S.	Shoot DW	10.79	3.49	0.116	12.04	Brown and Bernstein, 1953 (p. 44–46)
Kochia#, Sask.	*Kochia scoparia* (L.) Schrad.	Shoot DW	21.42	3.28	0.055	22.61	Steppuhn, 1990
New Mexico	*Kochia scoparia* (L.) Schrad.	Shoot DW	21.64	3.29	0.055	22.83	Steppuhn, 1990
Lovegrass‡‡‡	*Eragrostis sp.* N.M. Wolf	Shoot DW	7.60	2.65	0.128	8.58	Bernstein and Ford, 1959b (p. 39–44)
Orchardgrass	*Dactylis glomerata* L.	Shoot DW	9.20	2.38	0.094	10.07	Brown and Bernstein, 1953 (p. 44–46); Wadleigh et al., 1951
Ryegrass, perennial	*Lolium perenne* L.	Shoot DW	11.78	3.91	0.116	13.14	Brown and Bernstein, 1953 (p. 44–46)
Sesbania	*Sesbania exaltata* (Raf.) V.L. Cory	Shoot DW	9.08	2.60	0.107	10.05	Bernstein, 1956 (p. 33–34)
Sphaerophysa	*Sphaerophysa salsula* (Pall.) DC	Shoot DW	8.98	2.60	0.107	9.94	Francois and Bernstein, 1964 (p. 52–53)
Sudangrass	*Sorhum sudanense* (Piper) Stapf.	Shoot DW	14.00	2.50	0.065	14.92	Bower et al., 1970
Trefoil, Big	*Lotus pedunculatus* Cav.	Shoot DW	4.62	3.81	0.289	5.96	Ayers, 1948a,b (p. 23–25)
Trefoil, narrowleaf birdsfoot	*L. corniculatus* var *tenuifolium* L.	Shoot DW	9.63	4.33	0.152	11.09	Ayers, 1948a,b (p. 23–25); Ayers, 1950
Vetch, common	*Vicia angustifolia* L.	Shoot DW	7.20	3.34	0.168	8.41	Ravikovitch and Porath, 1967
Wheatgrass, crested, Common	*Agropyron sibiricum* (Willd.) Beauvois	Shoot DW	15.56	2.58	0.061	16.50	Bernstein and Ford, 1958 (p. 32–36)
Wheatgrass, crested Fairway	*A. cristatum* (L.) Gaertner	Shoot DW	14.32	4.50	0.105	15.82	Bernstein and Ford, 1958 (p. 32–36)
Wheatgrass, intermediate#	*Thinopyrum intermedium* (Host) Bark. and Dewey	Shoot DW	7.72	2.17	0.100	8.49	Steppuhn, 1997
Wheatgrass, slender#	*Elymus trachycaulus* (Link) Bark. and Dewey	Shoot DW	7.16	1.97	0.095	7.84	Steppuhn, 1997
Wheatgrass, tall	*Agropyron elongatum* (Hort) Beauvois	Shoot DW	18.92	3.35	0.065	20.13	Bernstein and Ford, 1958 (p. 32–36)
Wildrye, beardless	*Elymus triticoides* Buckl.	Shoot DW	10.65	2.65	0.091	11.62	Brown and Bernstein, 1953
			Vegetable, nut, and fruit crops				
Almond	*Prunus duclis* (Mill.) D.A. Webb	Shoot growth	3.83	3.03	0.289	4.94	Bernstein et al., 1956; Brown et al., 1953
Apricot	*Prunus armeniaca* L.	Shoot growth	3.39	3.45	0.366	4.63	Bernstein et al., 1956
Artichoke	*Cynara scolymus* L.	Bud yield	10.07	5.83	0.175	11.83	Francois, 1995
Asparagus	*Asparagus officinalis* L.	Spear yield	28.50	2.38	0.030	29.37	Francois, 1987
Bean, common	*Phaseolus vulgaris* L.	Seed yield	3.34	2.63	0.289	4.30	Bernstein and Ayers, 1951; Hoffman and Rawlins, 1970; Magistad et al., 1943; Nieman and Bernstein, 1959; Osawa, 1965
Bean, mung	*Vigna radiata* (L.) R. Wilcz.	Seed yield	3.91	3.43	0.315	5.15	Minhas et al., 1990
Beet, red¶¶	*Beta vulgaris* L.	Storage root	9.19	3.52	0.137	10.45	Bernstein et al., 1974; Hoffman and Rawlins, 1971; Magistad et al., 1943
Blackberry	*Rubus macropetalus* Doug. ex Hook	Fruit yield	3.48	3.20	0.335	4.64	Ehlig, 1964
Boysenberry	*Rubus ursinus* Cham. and Schlechtend	Fruit yield	3.48	3.20	0.335	4.64	Ehlig, 1964
Broccoli	*Brassica oleracea* L. (Botrytis Group)	Shoot FW	7.88	3.02	0.140	8.99	Bernstein and Ayers, 1949a (p. 39); Bernstein et al., 1974
Cabbage	*B. oleracea* L. (Capitata Group)	Head FW	6.62	2.66	0.148	7.60	Bernstein and Ayers, 1949a (p. 39); Bernstein et al., 1974; Osawa, 1965
Carrot	*Daucus carota* L.	Storage root	4.26	2.48	0.213	5.17	Bernstein and Ayers, 1953a; Bernstein et al., 1974; Lagerwerff and Holland, 1960; Magistad et al., 1943; Osawa, 1965
Celery	*Apium graveolens* L. var dulce (Mill.) Pers.	Petiole FW	9.49	2.45	0.094	10.39	Francois and West, 1982

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Table 6. Continued.

Crop		Tolerance§ based on	Nonlinear tolerance parameter				References
Common name	Botanical name‡		C_{50} (EC_e) dS/m	p Shape	*s* Steepness	Salinity tolerance index	
Corn, sweet	*Zea mays* L.	Ear FW	5.54	2.75	0.183	6.56	Bernstein and Ayers, 1949b (p. 41–42)
Cowpea	*Vigna unguiculata* (L.) Walp.	Seed yield	8.71	4.91	0.183	10.30	West and Francois, 1982
Cucumber	*Cucumis sativus* L.	Fruit yield	6.02	3.29	0.198	7.21	Osawa, 1965; Ploegman and Bierhuizen, 1970
Date palm	*Phoenix dactylifera* L.	Fruit yield	17.42	2.60	0.055	18.38	Furr and Armstrong, 1962; (p. 11–13); Furr and Ream, 1968; Furr et al., 1966
Eggplant	*Solanum melongena* L. var *esculentum* Nees.	Fruit yield	7.99	2.32	0.105	8.83	Heuer et al., 1986
Garlic	*Allium sativum* L.	Bulb yield	7.06	4.65	0.218	8.59	Francois, 1994b
Grape	*Vitus vinifera* L.	Shoot growth	6.38	2.54	0.146	7.31	Groot Obbink and Alexander, 1973; Nauriyal and Gupta, 1967; Taha et al., 1972
Grapefruit	*Citrus* × *paradisi* Macfad.	Fruit yield	4.59	2.57	0.206	5.54	Bielorai et al., 1978
Guava	*Psidium guajava* L.	Shoot and root growth	9.43	4.09	0.149	10.84	Patil et al., 1984
Guayule	*Parthenium argentatum* A. Gray	Shoot DW	12.60	9.27	0.177	14.83	Maas et al., 1988
		rubber yield	12.03	7.23	0.164	14.01	
Lemon	*Citrus limon* (L.) Burm. F.	Fruit yield	5.09	2.70	0.195	6.08	Cerdá et al., 1990
Lettuce	*Lactuca sativa* L.	Top FW	4.83	2.60	0.198	5.79	Ayers et al., 1951; Bernstein et al., 1974; Osawa, 1965
Muskmelon	*Cucumis melo* L. (Reticulatus Group)	Fruit yield	6.62	2.33	0.128	7.46	Mangal et al., 1988; Shannon and Francois, 1978
Onion (bulb)	*Allium cepa* L.	Bulb yield	4.02	2.66	0.244	5.00	Bernstein and Ayers, 1953b; Bernstein et al., 1974; Hoffman and Rawlins, 1971; Osawa, 1965
Onion seed	*Allium cepa* L.	Seed yield	6.91	2.32	0.122	7.75	Mangal et al., 1989
Orange	*Citrus sinensis* (L.) Osbeck	Fruit yield	4.80	2.61	0.200	5.76	Bielorai et al., 1988; Bingham et al., 1974; Dasberg et al., 1991; Harding et al., 1958
Pea	*Pisum sativum* L.	Seed FW	7.77	3.50	0.161	9.02	Cerdá et al., 1982
Peach	*Prunus persica* (L.) Batsch	Shoot growth, fruit yield	3.78	3.35	0.320	4.99	Bernstein et al., 1956; Brown et al., 1953; Hayward et al., 1946
Pepper	*Capsicum annuum* L.	Fruit yield	4.76	2.76	0.213	5.77	Bernstein, 1954 (p. 36–37); Osawa, 1965; USSL§§§
Plum; prune	*Prunus domestica* L.	Fruit yield	3.91	6.34	0.472	5.76	Hoffman et al., 1989
Potato	*Solanum tuberosum* L.	Tuber yield	5.54	2.75	0.183	6.56	Bernstein et al., 1951
Purslane	*Portulaca oleracea* L.	Shoot FW	11.12	5.08	0.146	12.74	Kumamoto et al., 1992; Grieve and Suarez, 1997
Radish	*Raphanus sativus* L.	Storage root	4.73	2.55	0.198	5.67	Hoffman and Rawlins, 1971; Osawa, 1965
Spinach	*Spinacia oleracea* L.	Top FW	8.22	2.59	0.116	9.18	Langdale et al., 1971; Osawa, 1965
Squash, scallop	*Cucrbita pepo* L. var *melopepo* L. Alef.	Fruit yield	5.60	4.31	0.244	7.46	Francois, 1985
Squash, zucchini	*C. peop* L. var *melopepo* (L.) Alef.	Fruit yield	9.29	4.42	0.160	10.78	Francois, 1985; Graifenberg et al., 1996
Strawberry	*Fragaria* × *ananassa* Dutch.	Fruit yield	2.23	3.07	0.503	3.36	Ehlig and Bernstein, 1958; Osawa, 1965
Sweet potato	*Ipomoea batatas* (L.) Lam.	Fleshy root	5.72	2.61	0.168	6.68	Greig and Smith, 1962; USSL§§§
Tomato	*Lycopersicon lycopersicum* (L.) Karst. ex Farw. [syn. *Lycopersicon esculentum* Mill.]	Fruit yield	7.21	2.96	0.151	8.29	Bierhuizen and Ploegman, 1967; Hayward and Long, 1943, Lyon, 1941; Shalhevet and Yaron, 1973
Tomato, cherry	*L. lycopersicum* var. *Cerasiforme* (Dunal) Alef.	Fruit yield	6.86	2.59	0.139	7.81	Caro et al., 1991
Turnip	*Brassica rapa* L. (Rapifera Group)	Storage root	6.13	2.32	0.137	6.97	Francois, 1984
Turnip (greens)	*Brassica rapa* L.	Top FW	13.50	2.58	0.065	15.45	Francois, 1984

FW = fresh weight; DW = dry weight.

† Table based on Table 3–1, Maas and Grattan, 1999, and controlled tests of crop-yield response to increasing root-zone salinity gradually applied to the plants as early seedlings. These data are applicable when rootstocks of woody crops are used that do not accumulate Na^+ or Cl^- rapidly or when these ions do not predominate in the soil.

‡ Botanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.

§ In gypsiferous soils, plants will tolerate about 5–10% greater salinity than indicated.

¶ Less tolerant during seedling stage, EC_e at this stage should not exceed 4 or 5 dS/m.

These data are based on tests following dryland agricultural practices, where seeds are planted directly in saline seedbeds.

†† These values for p were obtained from $Fn(p) = bC_t$ of Fig. 5.

‡‡ Grain and forage yields of DeKalb XL-75 grown on an organic muck soil decreased about 26% per decisiemen/meter above a threshold of 1.9 dS/m (Hoffman et al., 1983).

§§ Because paddy rice is grown under flooded conditions, values refer to the electrical conductivity of the soil water while the plants are submerged. Less tolerant during seedling stage.

¶¶ Sensitive during germination and emergence, EC_e should not exceed 3 dS/m.

Data from one cultivar, Probred.

††† Average of several varieties. Suwannee and Coastal are about 20% more tolerant, and common and Greenfield are about 20% less tolerant than the average.

‡‡‡ Average for Boer, Wilman, Sand, and Weeping cultivars (Lehmann seems about 50% more tolerant).

§§§ Unpublished U.S. Salinity Laboratory data.

±10% error limit of the actual was again used. The selected-line-segments method recorded b-to-s conversions within this limit for five out or the eight test experiments (Table 5). The fitted Fn(p) × exp(bC_t) with $s = \ln p/(C_{50})$ and the fitted $s \times (b)$ methods respectively registered seven and eight out of eight test experiments within an error of ±10% or less. Within an error limit of ±5% of the actual, the three methods [selected-line-segments, s fitted × (b), Fn(p) fitted × (bC_t), with $s = \ln p/(C_{50})$], respectively. recorded four, seven, and six test experiments out of the eight.

One of the most recent published lists of agricultural crop tolerances to root-zone salinity is arrayed according to four crop groups: "fiber-grain-special," "grasses-forage," "vegetable-fruit," "woody" (Tables 3-1 and 3-2, Maas and Grattan, 1999). The threshold and slope values listed for each crop in these tables were converted to C_{50}, s, p, and the ST-Index using the regression fits of $C_{50} \times (C_{\text{mid}})$ and $s \times (b)$, and the relationships of $p = \exp(sC_{50})$ and ST-Index $= C_{50} + sC_{50}$, respectively (Table 6). The parameter values in Table 6 also include those obtained in crop-yield response tests conducted under dryland agricultural conditions, where seeds were placed directly into salinized seedbeds.

DISCUSSION

Many factors influence the yield of agricultural crops besides the response to increasing root-zone salinity (Maas and Grattan, 1999; Steppuhn et al., 2005). In view of the myriad of influences which affect the relationship of product yield with salinity, a single-value index of crop tolerance to root-zone salinity would seem appropriate and useful for comparing agricultural crops. The ST-Index, based on the nonlinear parameters of C_{50} and s (Eq. [4]), fills this need. This index identifies a salinity value equal to the 50% reduction in crop yield from that of the nonsaline yield plus a measure of the tendency to maintain some product yield as the crop is subjected to increasing salinity levels approaching C_{50}, that is, ST-Index $= C_{50} + sC_{50}$.

The concept of an index for rating the salinity tolerance of agricultural crops was followed earlier (Ayers et al., 1951; U.S. Salinity Laboratory Staff, 1954; Brown and Hayward, 1956). The practice then was to simply use C_{50} as the index. Now, with the benefit of the modified discount response function (Eq. [2]), we propose adding the term, sC_{50}, to the earlier index. Although simple, the ST-Index shows sensitivity. For example, testing with canola demonstrates a salinity tolerance approaching that of barley, *Hordeum vulgare* L. (Francois, 1994a; Steppuhn et al., 2002). Under dryland agricultural practices, the ST-Indices for *Brassica napus* L. canola and barley grain crops equal 8.00 and 8.29, respectively (Table 6). Under irrigation-agricultural practices, the respective ST-Index-values equal 17.27 and 18.87. These indices also show the pronounced effects of seeding into saline seedbeds, as required in dryland agriculture, compared to seeding where fresh water is applied to establish the crop under irrigated cultivation.

Maas (1990) and Maas and Grattan (1999) stated that several nonlinear models, including Eq. [3], more accurately describe the actual response of plant crops to salinity than the threshold-slope linear model (Eq. [5]). Extension personnel and plant growth modelers need to work with a more precise nonlinear response analog. However, all but one of the crop lists available to them are based on a linear response. Table 6 offers an alternative list based on the nonlinear discount function. Also, as information becomes available on the response of crops to irrigation with saline water containing various specific ions, response values under these conditions can be incorporated into Table 6. In cases where only estimates of C_{50} are available, van Genuchten and Gupta (1993) suggest an assumption that $p \approx 3.00$ ($s \approx 1.099/C_{50}$). Or, one could let ST-Index $\approx C_{50}$, resulting in an index with a lower value.

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