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A JOURNAL OF AGRICULTURAL SCIENCE PUBLISHED BY
THE CALIFORNIA AGRICULTURAL EXPERIMENT STATION

Volume 54 • Number 1 • January 1986

Simulated Crop-Water Production Functions for Several Crops When Irrigated with Saline Waters

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ABSTRACT

Information on crop-water production functions when irrigating with saline waters is required to develop optimum irrigation strategies for various crops. A model was developed to compute these production functions by combining three relationships: yield and evapotranspiration, yield and average root-zone salinity, and average root-zone salinity and leaching fraction. The model allows plant-growth adjustment, and therefore evapotranspiration adjustment, to root-zone salinity. Using the model, product functions were computed for several crops. Calculated relative yields were compared with measured relative yields from experiments that had water quality and quantity as variables. Reasonable agreement between the two values provides some assurance of the model's utility and reported production functions under field conditions.

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ACKNOWLEDGMENT

This study was supported by the University of California Kearney Foundation of Soil Science.

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INTRODUCTION

DEVELOPMENT OF SOIL SALINITY occurs as part of the irrigation-evapotranspiration process. The necessity of adding water in excess of evapotranspiration (ET) to provide leaching under these conditions has long been recognized. The question is: How much leaching is appropriate? The leaching requirement has been defined as the fraction of the irrigated water that must be leached through the root zone to control soil salinity at any specified level (U.S. Salinity Laboratory Staff, 1954). The specified level has commonly been understood to be that level which will allow maximum crop production. However, the common goal of an agricultural enterprise is to maximize profits and maximum production may not always coincide with maximum profit. This is particularly true under conditions of water scarcity or where drainage systems must be installed. For example, some areas, such as California's San Joaquin Valley, do not have natural disposal sites for drainage water so construction of evaporation ponds may be required. In some cases productive land must be sacrificed for the building of evaporation ponds. Under these conditions optimal water management could be significantly different than management to maximize crop production (Dinar, Letey, and Knapp 1985).

Information on a crop-water production function is required to develop optimum irrigation management strategies. The crop-water production function will be unique for each crop, as crops vary in sensitivity to salinity. A model has been developed (Letey, Dinar, and Knapp 1985) that can be used to formulate crop-water production functions when irrigating with saline waters. This report will provide crop-water production functions computed from the model for several crops. The first section will provide details of the model development; the following sections will provide crop-water production functions for individual crops and then a comparison between model predictions and experimental data for some crops.

CROP-WATER PRODUCTION FUNCTION MODEL

A linear relationship between yield and ET is assumed. Strong experimental evidence supports a linear relationship between yield and ET for forages or total top weight of nonforages (Davis 1983; Downey 1972; Hanks, Gardner, and Florian 1969; Hanks and Retta 1980; Power et al. 1973; Sammis et al. 1979). A linear relationship between the marketable part of the crop and ET has been reported for several nonforage crops such as corn, *Zea mays;* wheat, *Triticum aestivum;* sugarbeets, *Beta vulgaris,* and potatoes, *Solanum tuberosum* (Beese, Horton, and Werenga 1982; Stewart et al. 1977; Miller and Hang 1982; Hanks 1982; Shalhevet, Shimshi, and Meir 1983). The relationship between

[1]Accepted for publication October 3, 1985.

yield (Y_{ns}) and seasonal-applied water (AW) for nonsaline irrigation water is illustrated in figure 1. The seasonal-applied water includes preplant irrigation and precipitation which contributes to the water available to the crop. The yield-ET and yield-AW relationships are assumed to be identical for AW values less than ET_{max}. Applying water at less than ET_{max} results in deficit irrigation so the assumption is valid as long as excess water resulting in deep percolation is not applied at any irrigation. Maximum ET is associated with maximum attainable yield (Y_{max}), when water is not limiting. Fertilization and other management factors are assumed to be adequate so that yields remain constant for AW greater than ET_{max}.

Consideration is now given to applying saline irrigation water to the crop, which has a production function for nonsaline water as depicted in figure 1. Assume AW is less than ET_{max} and equal to AW_l. Initially, no leaching occurs and salts accumulate due to transpiration until the root-zone salinity is sufficient to cause a yield decrement (YD). The yield decrement results in smaller plants and a consequent decrease in ET. The YD depicted in figure 1 results in ET_l. The difference between AW_l and ET_l is deep percolation (DP) which contributes to leaching of salts from the root zone. Ultimately, YD is large enough so that sufficient leaching occurs to mitigate further yield decrements and a steady-state condition exists. The following development allows the calculation of YD (and therefore yield) for various values of AW when irrigation is done with waters of various salinities.

The relationship between YD and DP is

$$YD = (DP)S \qquad \text{for } AW_t < AW < ET_{max} \tag{1}$$

where S is the slope of the production function for nonsaline irrigation water. Maas and Hoffman (1977) proposed a relationship between relative yield and average root zone salinity (expressed in electrical conductivity of saturated soil extract, EC_e) as

$$\text{Relative yield} = 100 - B(EC_e - C') \tag{2}$$

where C' is threshold salinity and B is the slope of the yield-salinity curve at EC_e values greater than C'.

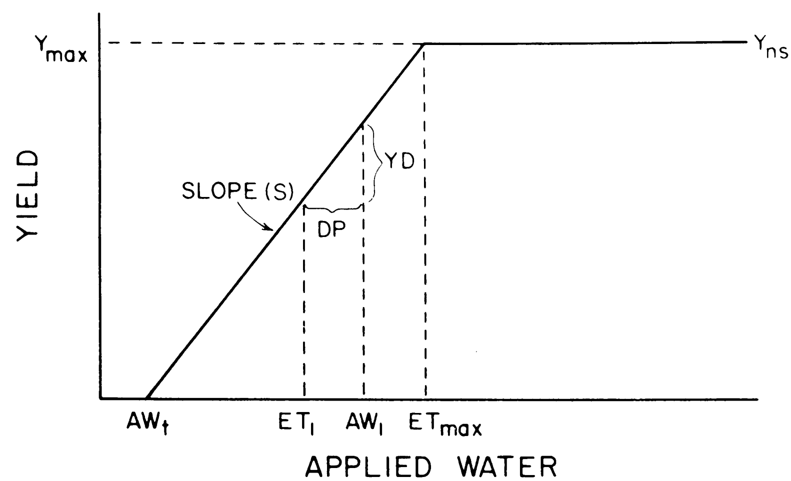

Fig. 1. Relationship between yield (Y_{ns}) and seasonal-applied nonsaline water (AW). Evapotranspiration (ET) is equal to AW for AW values equal to or less than ET_{max}. Other symbols are described in the text.

By definition

$$\text{Relative yield} = 100\,(Y_{ns} - YD)/Y_{ns} \tag{3}$$

where Y_{ns} is the yield resulting from irrigating with nonsaline water. Substitution of equation (2) into (3) and rearranging results in

$$EC_e = C' + 100\,YD/BY_{ns} \qquad \text{for } Y_{ns} \geq YD \geq 0 \tag{4}$$

A relationship between EC_e and irrigation water salinity (EC_i) is required. Hoffman and van Genuchten (1983) present relationships between EC_e and EC_i for three water uptake functions, and any of the cases could be used. However, the authors report that the exponential uptake function, as first proposed by Raats (1974), gave the best agreement with experimental data, so this relationship will be used. The equation for exponential water uptake function is

$$2EC_e/EC_i = 1/L + (\delta/ZL)\ln[L + (1-L)\exp(-Z/\delta)] \tag{5}$$

where L is the leaching fraction, Z is the depth of the root zone, and δ is a factor in the exponential uptake function. Hoffman and van Genuchten (1983) suggest that δ equals 0.2 Z; therefore, both δ and Z drop out of equation (5). (Note that these authors used soil solution EC, whereas here saturated soil extract (EC_e) is used and EC_e is assumed to equal EC/2.)

By definition and using relationships depicted in figure 1

$$L = DP/AW = YD/(AW)S \qquad \text{for } AW_t < AW < ET_{max} \tag{6}$$

The latter relationship of equation (6) is substituted into equation (5) for L. From figure 1:

$$Y_{ns} = S(AW - AW_t) \qquad \text{for } AW_t < AW < ET_{max} \tag{7}$$

Equation (7) is substituted into equation (4) for Y_{ns}. Finally equation (4) is substituted into equation (5) for EC_e resulting in

$$\frac{100(YD)^2}{B\,S(AW - AW_t)} + (YD)C' - \frac{EC_i(S)(AW)}{2} - 0.1\,EC_i(S)(AW)\ln\left[\frac{YD}{(AW)S} + \left(1 - \frac{YD}{(AW)S}\right)\exp(-5)\right] = 0 \tag{8}$$

Equation (8) can be used to calculate YD for given values of AW of irrigation water salinity, EC_i, for the range $AW_t < AW < ET_{max}$.

Y_{ns} equals Y_{max} for $AW \geq ET_{max}$ so Y_{max} is substituted into equation (4) for these conditions. Deep percolation is $(AW - ET_{max} + YD/S)$ for $AW \geq ET_{max}$ and

$$L = 1 - ET_{max}/AW + YD/(AW)S \tag{9}$$

Equation (9) is substituted into equation (5). Again substituting equation (4) into equation (5) results in

$$C' + \frac{100\,YD}{BY_{max}} - \frac{0.5\,EC_i}{1 - \dfrac{ET_{max}}{AW} + \dfrac{YD}{(AW)S}}$$

$$-\frac{0.1\ EC_i}{1-\frac{ET_{max}}{AW}+\frac{YD}{(AW)S}}\ln\left\{1-\left[\frac{ET_{max}}{AW}-\frac{YD}{(AW)S}\right]\left[1-\exp(-5)\right]\right\}=0 \qquad (10)$$

Equation (10) can be used to calculate YD, resulting from using given values of AW of irrigation water salinity, EC_i, when AW $\geq ET_{max}$. Values of C′ and B to be used in equation (8) or (10) for various crops are available from tables presented by Maas and Hoffman (1977). The crop-water production function must be known for a given crop irrigated with nonsaline water to determine values of S, ET_{max} and Y_{max}. The values of YD calculated from equations (8) and (10) can be used in equations (6) and (9) respectively to calculate L for various values of AW. Solutions to equations (8) and (10) were obtained by the Newton-Raphson procedure for numerical solutions of nonlinear equations (Ralston and Rabinowitz 1978).

Equations (8) and (10) allow the computation of production functions in terms of absolute values of yields and applied water appropriate for the experimental site at which the input data were measured. Crop-water production functions are often expressed in relative terms to help in transferring the relationships among geographical areas of differing climates and growing conditions. Production functions reported in this publication will be scaled to facilitate application to regions other than the experimental sites which were selected for input data. Yields will be reported on a relative basis (RY) with a value of 1.0 representing maximum yield. The seasonal values of ET and AW were scaled by the seasonal pan evaporation (E_p). Operationally, this was accomplished by dividing Y_{max} and YD in equations (8) and (10) by the experimentally determined value of Y_{max} and by dividing ET_{max} and AW in these equations by E_p from the experimental site. A scaled value for S was similarly used in the equations.

PROCEDURES

Crops were selected for which experimentally determined relationships between yield and ET had been reported. Specifically, values for Y_{max}, ET_{max}, AW_t, and E_p were required. Information on most of the crops analyzed are summarized in table 1. A special treatment was necessary for cotton which will be discussed later; therefore, it is excluded from table 1. The parameters were scaled as described above and used in equations (8) and (10) to compute YD (and therefore RY) for a range of AW/E_p and EC_i which can be tabulated or graphically displayed. Computed relationships between RY and AW/E_p for given values of EC_i will be graphically displayed for each crop which was investigated.

For many purposes it is more convenient to use a continuous equation which describes the relationships between variables than to use tabular or graphical data. Thus, a multiple regression analysis was applied to fit curves to the computed points. RY and L were determined as functions of AW/E_p and EC_i for the whole set of values and also as functions of AW/E_p for individual values of EC_i. The functional forms tested were linear, log-log, and quadratic. The r^2 values were determined for each functional form. The quadratic estimations gave the best fit (highest values of r) for all cases, so these will be the only equations reported.

The equation relating RY to AW/E_p and EC_i will be given along with the graphical display of results for each crop. The functional relationship between RY and AW/E_p for

TABLE 1. VALUES USED AS INPUT TO THE CROP-WATER PRODUCTION FUNCTION MODEL

Crop	Y_{max}	ET_{max}	AW_t	E_p	C′*	B*	Reference
	(Mg/ha)	(cm)	(cm)	(cm)			
Alfalfa	18.0	80.0	0	106	2.0	7.3	Hanks and Retta (1980)
Cauliflower	186†	23.2	6.5	28.8	2.8‡	9.2‡	Jobes, Hoffman, and Wood (1981)
Celery	1052†	46.2	20.5	54.9	1.8	6.2	Hoffman and Jobes (1983)
Corn	11.6	67.4	7.0	106	1.7	12.0	Stewart et al. (1977)
Cowpea	3.2	62.8	28.6	81.6	4.9	12.0	Hoffman and Jobes (1983)
Lettuce	793†‡	24.9‡	13.4	46.2	1.3	13.0	Hoffman et al. (1979)
Oats	9.1‡	52.2	8.7	63.7	2.2‡	7.0‡	Jobes, Hoffman, and Wood (1981)
Sugarbeet	71.5	80.0	25.0	115	3.4	1.6	Hanks (1982)
Sugarbeet	71.5	80.0	25.0	115	7.0	5.9	Hanks (1982)
Tomato	85.0	82.0	42.0	110	2.5	9.9	Jobes, Hoffman, and Wood (1981)
Wheat	15.0‡	46.9	26.1	72.0	6.1‡	3.2‡	Hoffman et al. (1979)

*Values from Maas and Hoffman (1977) except for C′ = 3.4 and B = 1.6 for sugarbeet and values for wheat which are the result of more recent studies by Maas (personal communication).
†Units of gm/plant.
‡See text for qualifying statements.

specific values of EC_i are presented in Appendix A and the functional relationship relating L to AW/E_p and EC_i are presented in Appendix B. The functional relationship between DP and AW/E_p and/or EC_i can be obtained by multiplying the functional relationship for L by AW. Likewise, the salinity of the drainage water leaving the root zone, EC_d, can be determined by EC_i/L, assuming no precipitation or dissolution of salts in the profile.

PRODUCTION FUNCTIONS

Alfalfa

A linear response between alfalfa (*Medicago sativa* L.) yield and ET for three alfalfa varieties was reported by Hanks and Retta (1980) from a study conducted at Logan, Utah. There was no appreciable difference in yield or ET due to variety. Although the investigation covered 2 years, only the second and third crops were harvested during the first year so we have selected the second-year data for the basic yield-ET relationship for our analysis.

The relationship between calculated relative yield and AW/E_p is plotted in figure 2 for irrigation waters of various salinities. The best fit equation relating relative yield to AW/E_p and EC_i is also given on figure 2. Functional relationships between RY and AW/E_p for specific values of EC_i are presented in Appendix A for all crops. Compared to irrigating

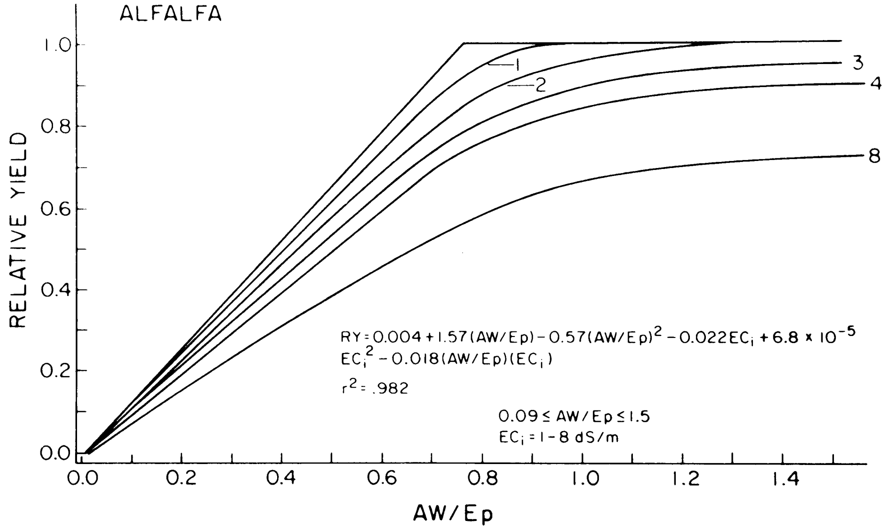

Fig. 2. Computed relative yields of alfalfa for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

with nonsaline water, a slight reduction in yield occurs at the intermediate values of AW when the irrigation water has an EC = 1. Yield reductions occur over all values of AW when irrigation waters have EC ≥ 3.

Relationships between leaching fraction, deep percolation, and electrical conductivity of the drainage water are plotted as functions of AW/E_p for various values of EC_i in figures 3, 4, and 5. The DP values illustrated in figure 4 are for the specific case of E_p equal to

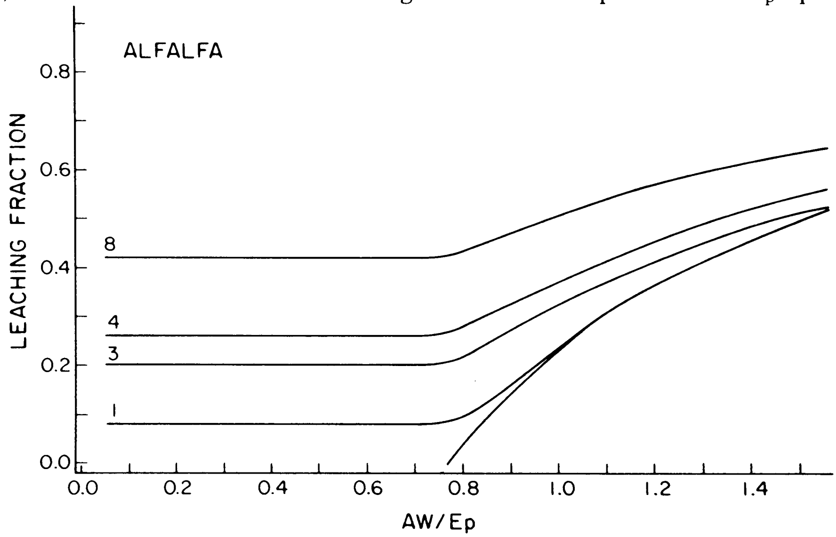

Fig. 3. Computed leaching fraction when alfalfa is irrigated with various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation water (dS/m).

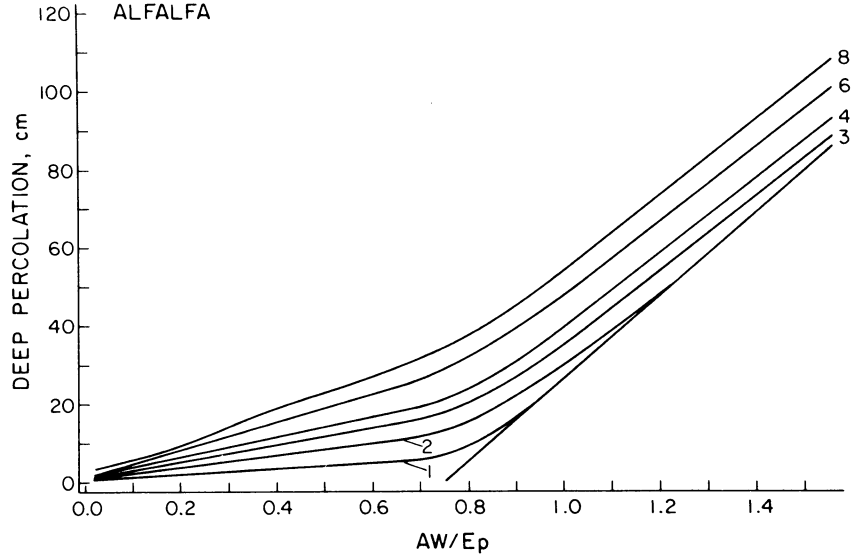

Fig. 4. Computed values of deep percolation when alfalfa is irrigated with various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation water (dS/m).

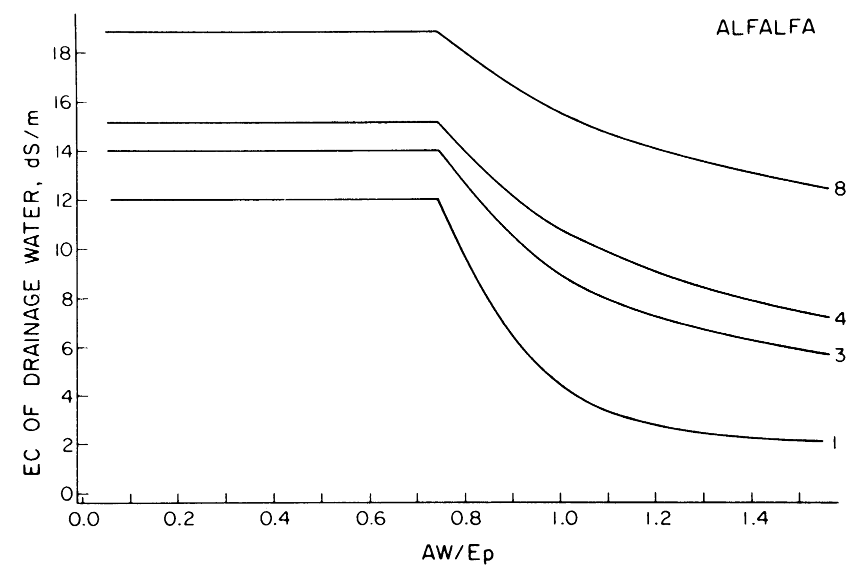

Fig. 5. Computed values of EC of the drainage water when alfalfa is irrigated with various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation water (dS/m).

106 cm. Some leaching occurs at all values of AW when saline irrigation waters are used and increases as the salinity of the irrigation water increases. Figures 3, 4, and 5 are presented to illustrate the typical computed relationships, but these relationships will not be graphically represented for other crops. The functional relationships between L and AW/E_p and EC_i are presented in Appendix B for all crops. Information on L can be converted to DP or EC of drainage water by techniques described in the Procedures section.

Cauliflower

A 2-year study (Jobes, Hoffman, and Wood 1981) was conducted on cauliflower *(Brassica oleracia).* We used the 2-year average data on marketable yield as input for our model. No salinity tolerance parameters were reported for cauliflower by Maas and Hoffman (1977). Values of C′ = 2.8 and B = 9.2 which were reported for broccoli, a closely related crop, were used in the model. The computed relative yields are plotted in figure 6 as functions of AW/E_p.

Celery

A 2-year study on irrigation of celery (*Apium graveolens* L.) with water of EC_i = 2.3 dS/m was conducted by Hoffman and Jobes (1983). Only the data for the second year (1980) were used as input data to compute the production functions because the celery plants were immature at harvest for the first year of the experiment. The calculated relative yields are plotted in figure 7 as a function of AW/E_p when the crop is irrigated with waters of various salinities.

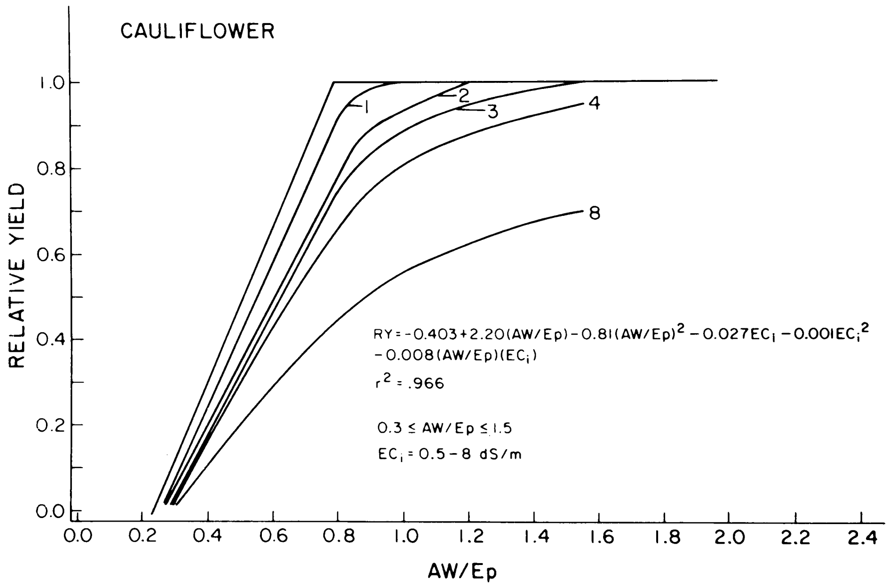

Fig. 6. Computed relative yields of cauliflower for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

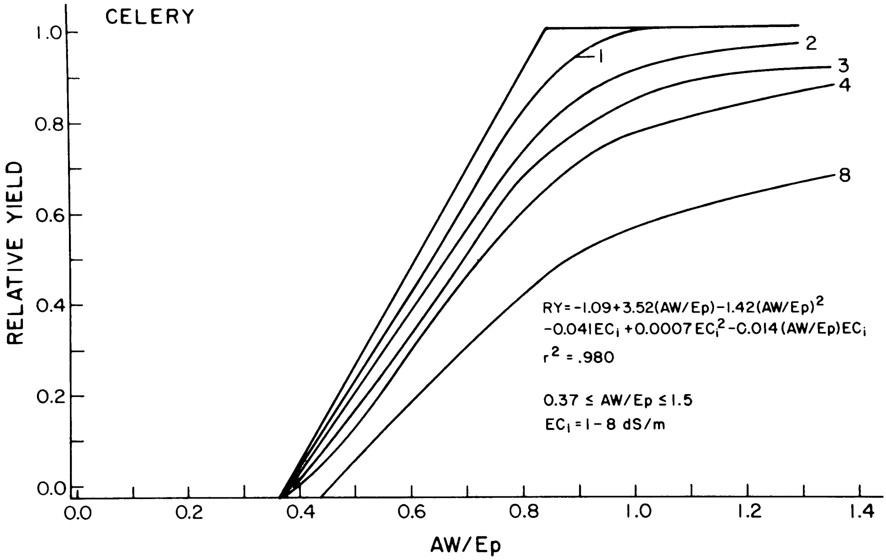

Fig. 7. Computed relative yields of celery for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

Corn

Stewart et al. (1977) reported results of a four-state study conducted on corn production as related to drought stress under irrigation. The data collected at Davis, California in 1974 were used for the basic input parameters for our model. The calculated relative yields are plotted in figure 8 as functions of AW/E_p when the crop was irrigated with waters of various salinities.

Cotton

Total cotton (*Gossypium hirsutum* L.) dry matter production is linearly related to ET but lint yield is not (Davis 1983; Grimes, Dickens, and Anderson 1969; Grimes, Yamada, and Dickens 1969). The crop-water production function model requires a linear relationship between production and ET. Thus, the model used here can only be used to compute crop-water production functions for total cotton dry matter. These functions can be transformed into cotton-lint production functions, if the relationship between total dry matter and lint yield is known.

The data of Davis (1983) were used as the basic input data for the model. The relationship between lint yield (Y^l) and total dry matter (Y^t) was obtained by combining the reported relationships between Y^l and ET and Y^t and ET with the result

$$Y^l = -0.361 + 0.194Y^t - 0.00489(Y^t)^2 \quad (11)$$

Davis (1983) reported Y^t_{max} = 19 Mg/ha, ET_{max} = 73 cm, AW_t = 9.8 cm, and E_p = 140 cm. Within the range of water application by Davis the cotton lint yield increased

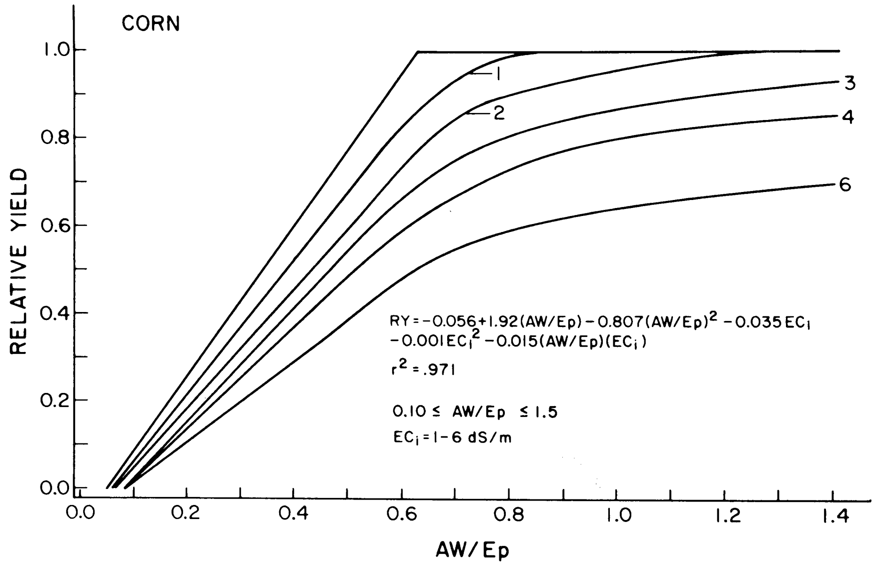

Fig. 8. Computed relative yields of corn for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

with increased ET and tended to plateau at the highest ET values. Thus, these input parameters result in a cotton-lint water production function with a plateau at high values of AW. There is evidence that very high water applications lead to very high total dry matter production, but a decrease in lint yield (Grimes, Dickens, and Anderson 1969; Grimes, Yamada, and Dickens 1969; Jackson and Tilt 1968). The investigation by Davis (1983) had the primary goal to investigate the effects of water deficits rather than "excess" water. Thus, it is possible that higher quantities of water application would have led to further increases in total dry-matter production but decrease in lint-yield production. A second case was analyzed for cotton to accommodate this possibility. The input parameters for this case were Y^t_{max} = 27.1 Mg/ha, ET_{max} = 100 cm, AW_t = 9.8 cm, and E_p = 140 cm. Distinction between the two cases will be made as follows: The former case, which is limited to the range of the experimental data, will be referred to as the production function with a plateau. The latter case, which projects the data to applied water values greater than used in the experiment, will be referred to as the quadratic production function because it leads to decreased lint production at high values of AW.

Salinity tolerance input data (C′ and B) are required. Unfortunately, the values reported by Maas and Hoffman (1977) relate only to cotton-lint yield. Because cotton-lint yield and total dry-matter production are not linearly related, the values of C′ and B appropriate for cotton lint are probably not appropriate for total dry-matter production. A search of the literature did not provide helpful information in evaluating values for B and C′ as they related to cotton total dry matter production.

Lacking direct experimental data, the following procedure was followed to estimate values for C′ and B for cotton dry matter production. Again, the data of Davis (1983) were used. Using C′ = 7.7 and B = 5.2 for cotton lint as reported by Maas and Hoffman (1977), the relationship between relative cotton-lint yield and EC_e is illustrated in figure 9. When the relative lint yield was 97, 93, and 81 percent, the corresponding relative total dry-matter production was 87, 79, and 63 percent, respectively. By placing the corresponding relative yields for lint and total dry matter production on figure 9 a curve was drawn to represent the corresponding relationship between relative total dry-matter production and EC_e. From this curve values of $C' = 6.1$ and $B = 6.9$ were calculated, and these are the values which were used in the computations for cotton.

The calculated relative cotton-lint yields are plotted as a function of AW/E_p when the crop is irrigated with waters of various salinities in figures 10 and 11 for the production function with a plateau and the quadratic production function, respectively. There is almost no effect of EC_i on lint yield until EC_i approaches 3 dS/m or greater. The lint yields are identical for the plateau and the quadratic production functions for AW/E_p values less than approximately 0.55. At higher values of AW/E_p there are significant differences in the production functions. Higher lint yields are predicted when irrigating with saline, as compared to nonsaline water, at very high values of AW/E_p and a quadratic function. This occurs because the salinity tends to inhibit the vegetative growth at high values of applied water, which leads to higher lint yields. These results are based on the premise that water transmission through the soil is nonlimiting and waterlogging does not occur.

The best-fit equation relating relative lint yield to AW/E_p and EC_i for production function with the plateau is given on figure 10. Relatively poor fit was achieved for the quadratic production function so no relationship will be presented for that case.

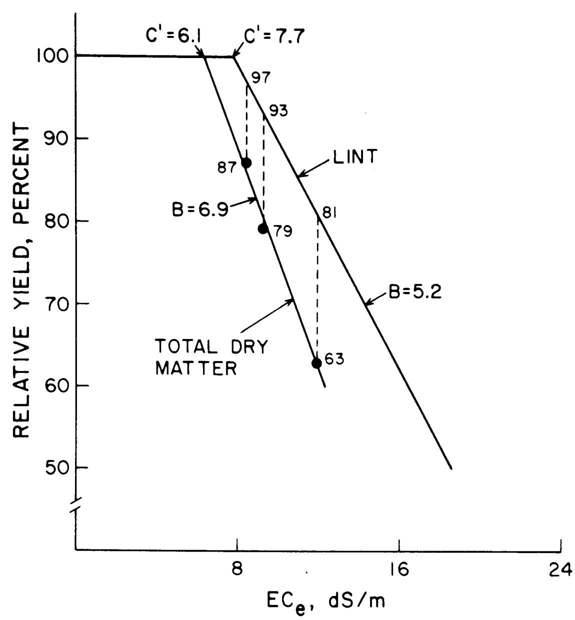

Fig. 9. Relationships between cotton lint and cotton total dry-matter yield to average root-zone EC_e. The curve for lint is from data of Maas and Hoffman (1977) and the curve for total dry matter was extrapolated from data of Davis (1983).

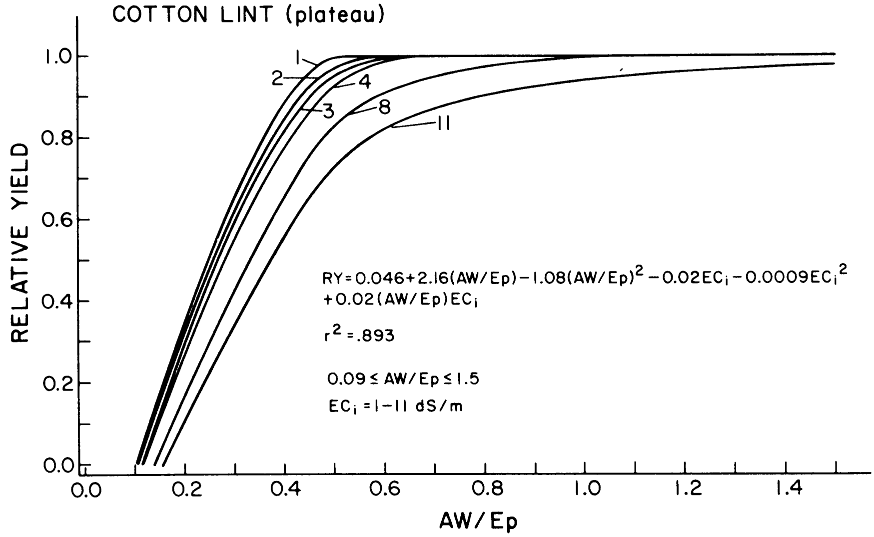

Fig. 10. Computed relative yields of cotton lint (plateau) for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

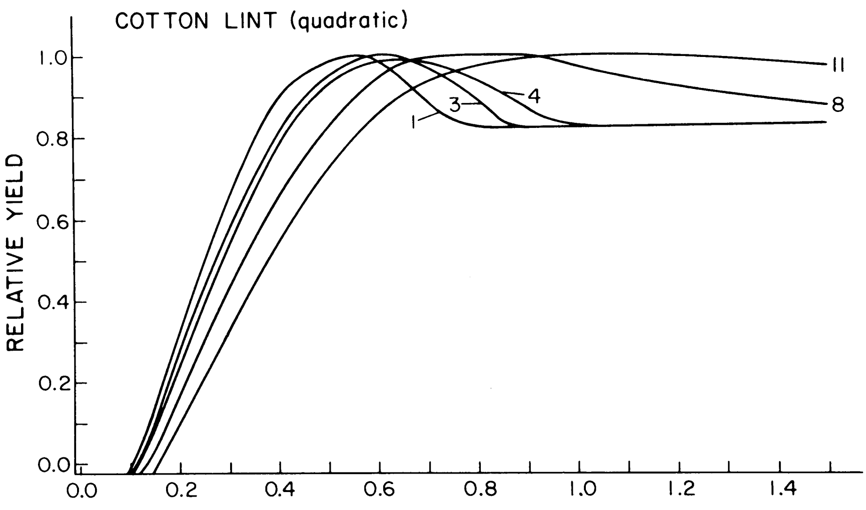

Fig. 11. Computed relative yields of cotton lint (quadratic) for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

Cowpea

Hoffman and Jobes (1983) conducted a study of irrigation of cowpea (*Vigna sinensis)* with irrigation waters of EC_i = 2.3 dS/m. Average values from the 2 years were used as input data to compute production functions. The calculated relative yields are plotted in figure 12 as functions of AW/E_p when the crop is irrigated with waters of various salinities.

Lettuce

Hoffman et al. (1979) conducted a study on irrigation of lettuce (*Lactuca sativa* L.) with water of E_i = 2.1 dS/m. The average values over the 3-year experiment were selected as input data to compute the production function. The specific values selected were Y_{max} = 619 g/plant, ET_{max} = 22.4 cm, E_p = 46.2 and AW_t = 13.4 cm.

Lettuce is a salt-sensitive crop, so some yield decrement was expected when irrigating with water EC equal to 2.1 dS/m as compared with irrigating with nonsaline water. The production function computed, using the above stated parameters, indicated that the highest experimental yield was 78 percent of maximum yield attainable with nonsaline water. Model input values were adjusted to be representative of nonsaline conditions. Specifically, Y_{max} equal to 793 (619/0.78) was used. ET_{max} was adjusted upwards, corresponding to the increase in Y_{max}. Equation (8) is valid for $AW < ET_{max}$ and equation (10) is valid for $AW \geq ET_{max}$. Thus, the main effect of adjusting the parameter values was to shift the range of AW values used in equations (8) and (10). This shift resulted in the different computed production functions illustrated in figure 13.

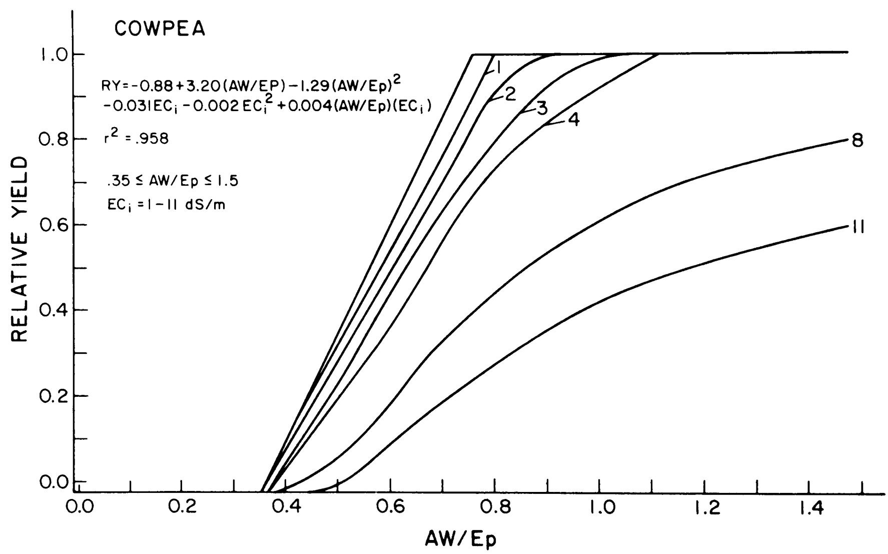

Fig. 12. Computed relative yields of cowpeas for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

Data have been used for several other crops which were achieved in experiments in which the irrigation water had EC value of 2.1 or 2.3 dS/m. Maximum yield from crops other than lettuce were computed to be 92 to 100 percent (depending on the specific crop) of yield achievable with nonsaline water. Adjustments on these crops as described above for lettuce resulted in negligible changes in the computed production functions.

Oats

Oats (*Avena sativa* L.) were grown for 2 years in the study by Jobes, Hoffman, and Wood (1981). A linear relationship between yield and ET was reported for oat forage over the entire ET range. A linear relationship between oat grain and ET was reported at the lower ETs, but the yield plateaued at the highest ET values. The model requires a linear relationship between yield and ET over the entire ET range; thus, the analysis was initially conducted on forage yield. The computed values of forage production (Y^f) were converted to grain yields (Y^g), using the following relationship which was determined from data reported by Jobes, Hoffman, and Wood (1981).

$$Y^g = 0.47\,(Y^f)^{0.78} \qquad r^2 = .799 \tag{12}$$

Average values for the 2-year study were selected for input to the model. Salt-tolerance parameters for oats were not reported by Maas and Hoffman (1977). Oats is considered moderately sensitive to salinity, so $C' = 2.2$ and $B = 7$, which are typical of moderately sensitive crops, were selected for the analysis. The calculated relative yields of grain and forage are plotted as functions of AW/E_p for various salinities in figures 14 and 15, respectively. Although the grain and forage yields resulting from different applications of

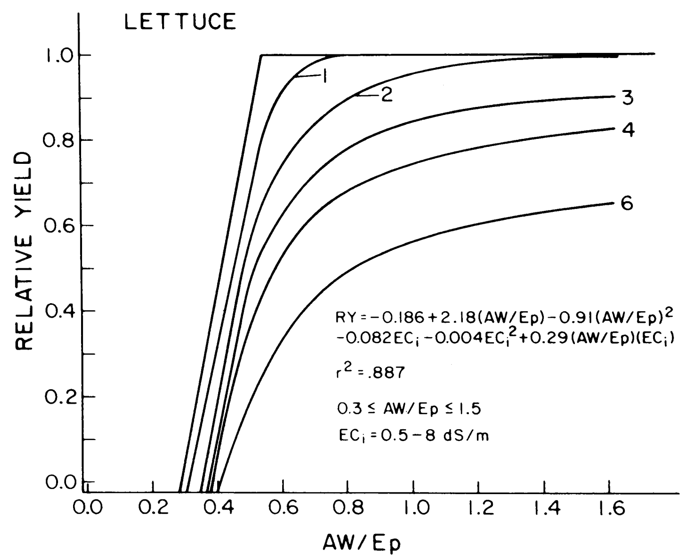

Fig. 13. Computed relative yields of lettuce for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

saline water (as illustrated in figures 14 and 15) appear similar, a direct comparison of the curves indicates that grain yields are slightly higher than forage yields for any given condition.

Sugarbeets

A four-state study was conducted on sugarbeet production as related to drought stress under irrigation (Hanks 1982). The data collected at Davis, California on root yields were used as the basic input numbers for the model. The authors stated that the highest irrigation level was to achieve a slight water deficit. Thus, we will assume that ET_{max} is 80 cm rather than 74, which was the highest irrigation applied in the experiment. Maas and Hoffman (1977) originally reported $C' = 7.0$ and $B = 5.9$ for sugarbeets. In more recent studies, values of $C' = 3.4$ and $B = 1.6$ have been found for sugarbeets (Maas, personal communication). The analysis was conducted using both sets of salinity tolerance values.

The calculated relative yield is plotted as a function of AW/E_p when the crop was irrigated with waters of various salinities in figure 16 for the case $C' = 3.4$ and $B = 1.6$. The relative effects of the two sets of salinity tolerance values on decrease of root yield caused by irrigating with saline waters are illustrated in figure 17. At lower values of AW/E_p the computed yield decrease was greater for $C' = 7.0$ and $B = 5.9$ than for $C' = 3.4$ and $B = 1.6$. The results at higher values of AW/E_p depended on the value of EC_i. At lower values of EC_i the computed yield decrease was greater for $C' = 3.4$ and $B = 1.6$ than for $C' = 7.0$ and $B = 5.9$. On the other hand, when $EC_i = 11$, the yield decrement over all values of AW was greater for the original as compared to the more recent salinity

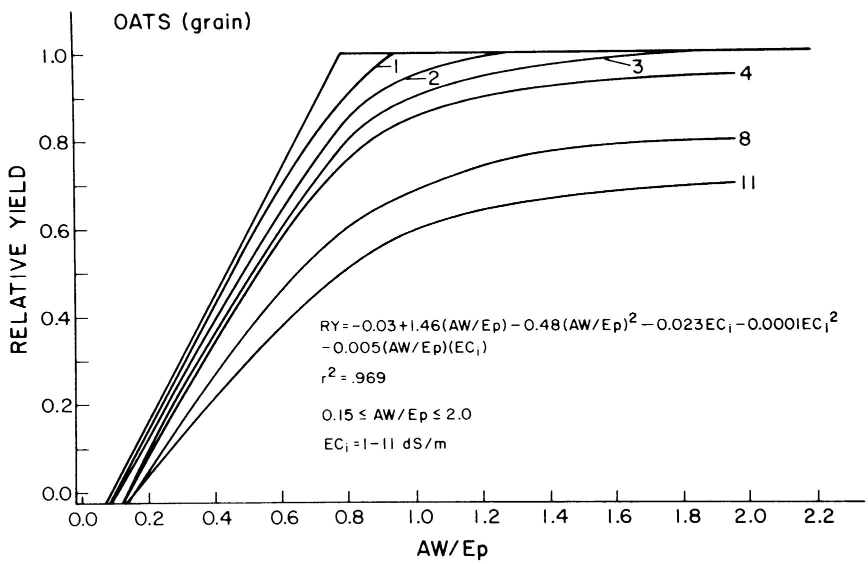

Fig. 14. Computed relative yields of oats (grain) for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

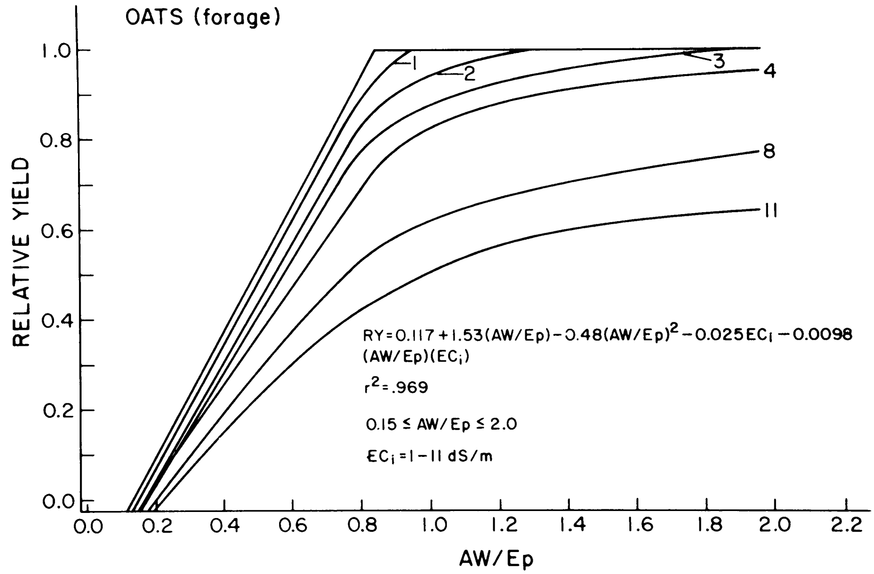

Fig. 15. Computed relative yields of oats (forage) for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

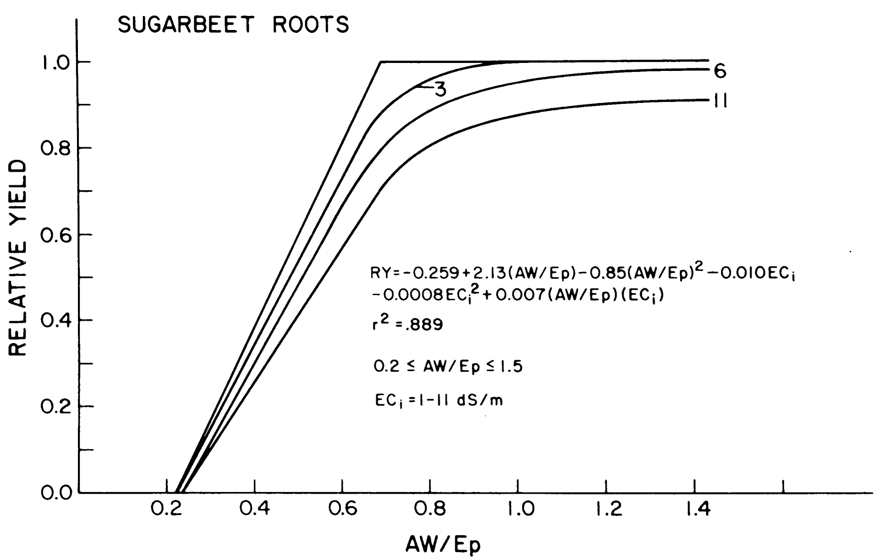

Fig. 16. Computed relative yields of sugarbeet roots for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

tolerance parameters. Results indicate that the values of both C′ and B are important in providing proper identification of crop salinity tolerance. Furthermore, the relative effect of these two parameters depends on the amount and EC_i of applied water. Note: If only the threshold value (C′) was considered in evaluating salinity tolerance of sugarbeets (or other crops), one would have been misled in expected yield decrements for most values of AW and EC_i (fig. 17). Indeed, the value of B appears to be a better indicator of relative tolerance than C′ for most water salinities and application rates. This factor is particularly important in crop-breeding programs for enhancing salinity tolerance where appropriate criteria for selection are required.

Tomatoes

Jobes, Hoffman, and Wood (1981) conducted a study on irrigation of tomatoes (*Lycopersicon esculentum* L.) with water of $EC_i = 2.1$ dS/m. The average values over the 3-year experiment were selected as input data to compute the production functions. The calculated relative yields are plotted in figure 18 as a function of AW/E_p when the crop is irrigated with waters of various salinities.

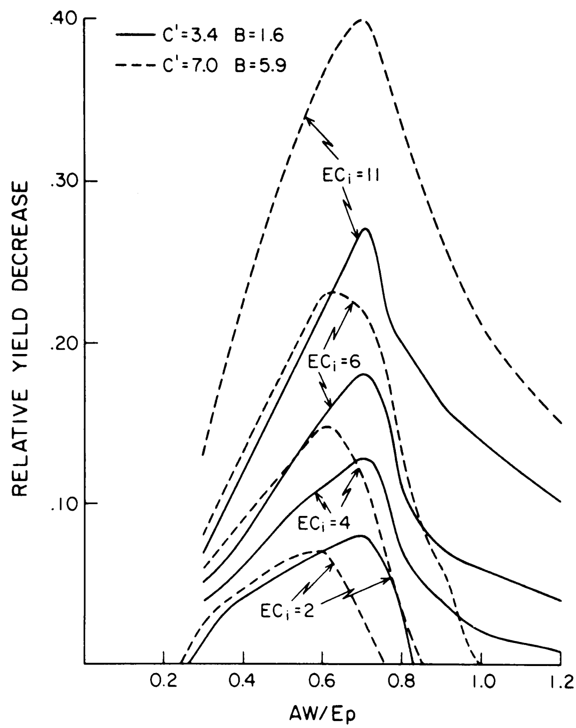

Fig. 17. Computed decrease in relative yield of sugarbeet roots resulting from irrigation with water of indicated EC relative to nonsaline water for two sets of crop-sensitivity values.

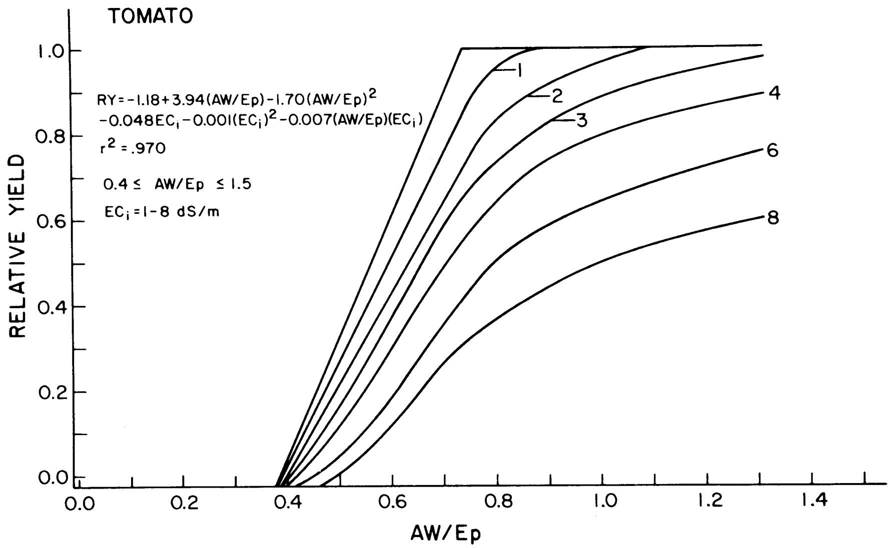

Fig. 18. Computed relative yields of tomato for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

Wheat

Hoffman et al. (1979) reported the results of a 3-year study on wheat (*Triticum aestivum* L.). An analysis of their data resulted in a higher linear correlation coefficient for forage yield (Y^f) and ET than for grain yield (Y^g) and ET. Production functions for wheat forage were therefore computed. The computed forage yields were converted to grain yields by the following relationship which was determined from the data reported by Hoffman et al. (1979).

$$Y^g = 2.15 + 0.175\, Y^f \qquad r^2 = .460 \tag{13}$$

The values used as input for the model are presented in table 1. The salinity tolerance coefficients for wheat of $C' = 6.1$ and $B = 3.2$ differ from those reported by Maas and Hoffman (1977), but they are the result of more recent experiments and are considered to be more accurate than the original numbers (Maas, personal communication). The calculated relative yields of forage and grain are plotted as functions of AW/E_p when the crop was irrigated with waters of various salinities in figures 19 and 20, respectively.

COMPARISON WITH EXPERIMENTAL DATA

Production functions can be developed by conceptual models, as was done in this report, or through experiments. Experimentally developed production functions have two disadvantages—they're time consuming and expensive. On the other hand, because field experiments more closely represent the conditions under which the production functions are to be used (growing agricultural crops), they are generally accepted as more valid than

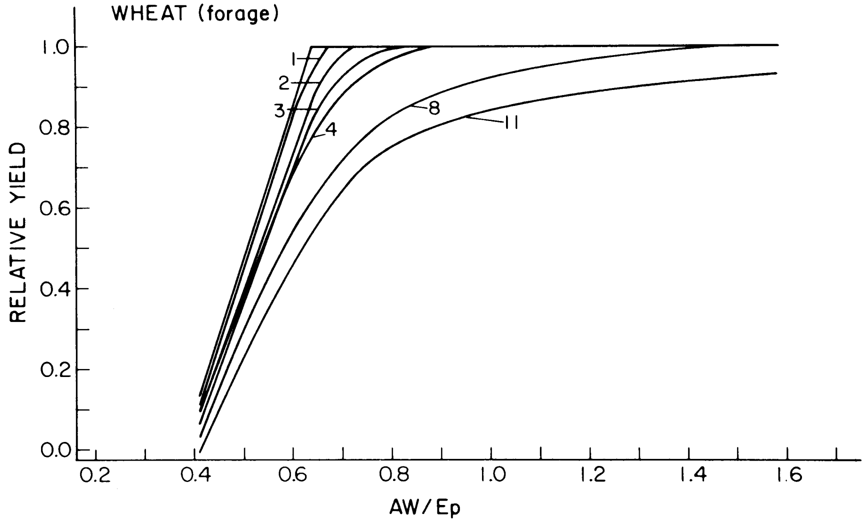

Fig. 19. Computed relative yields of wheat (forage) for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

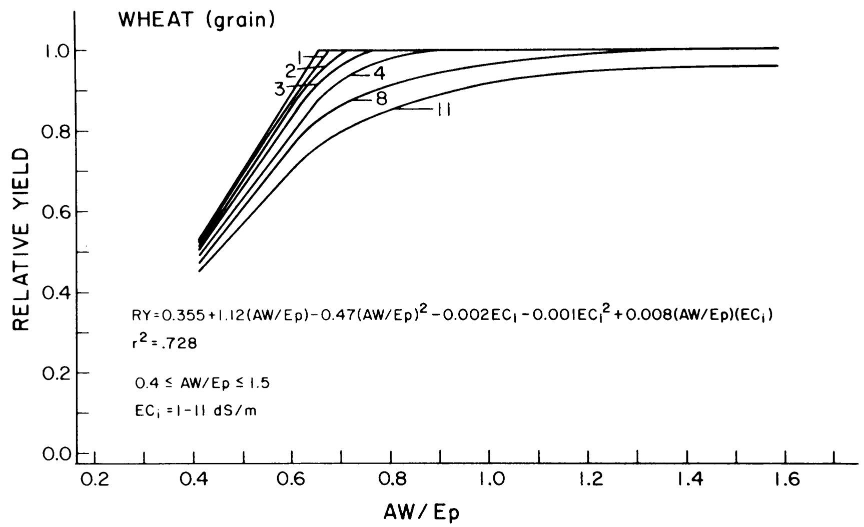

Fig. 20. Computed relative yields of wheat (grain) for various quantities of applied water which are scaled to pan evaporation. Each curve is for given EC of irrigation (dS/m).

model predictions. Indeed, the acceptability of models usually is predicated upon field validation of the model. Thus, comparisons between model predictions and measured experimental results will be considered here.

Few experiments have been conducted in which the variables were applications of various quantities and qualities of water. One extensive experiment was conducted by Hoffman, Jobes, and Alves (1983) using tall fescue (*Festuca elatior arundinacea* L.) as the test crop. The experimental variables consisted of three values of EC_i (1, 2.5, and 4 dS/m), three target values of L (0.09, 0.18, and 0.27), and three irrigation frequencies.

The variable L values resulted in variable applications of water quantities to different plots. This experiment was conducted in a rhizotron consisting of fully enclosed soil plots on which the amounts of applied and drainage waters were carefully controlled and accurately measured. The study was conducted for 3 years. The fescue was periodically harvested and the results were recorded for cumulative annual yield as well as annual quantities of irrigation and drainage water. The reported annual AW and the appropriate EC_i were used in equations (8) and (10) to calculate yield for each experimental plot for each year and the results were compared to measured yields.

A detailed comparison between measured and calculated yields from this experiment was reported by Letey, Dinar, and Knapp (1985) which will not be completely repeated here. In summary, the correlation coefficient between the predicted and measured yields was 0.73 which was significant at the 0.01 level. The average calculated yield from all plots was within 1 percent of the average measured yields from all plots, indicating that the model did not tend to overpredict or underpredict results. The average percent difference between predicted and calculated yields for individual plots was 8.1. Disaggregation of the data for given values of EC_i, L, and irrigation frequency indicated that the model generally predicted the yields equally well for all values of EC_i, L, or irrigation frequency.

Several crops were experimentally irrigated with various quantities of water which had an EC of either 2.1 or 2.3 (Hoffman et al. 1979; Jobes, Hoffman, and Wood 1981; Hoffman and Jobes 1983). These experiments provided the basic relationships between ET and yield which were used in developing the production functions for several crops reported in this paper. A comparison between the calculated and measured relative yields for the various crops is illustrated in figure 21. The data, as illustrated in figure 21, suggest that the model neither consistently overpredicts nor consistently underpredicts the measured results. Furthermore, there is reasonable agreement between measured and calculated values for the range of relative yield values from approximately .3 to 1.

The correlation coefficient and average difference between calculated and measured values for the various values of applied water for the various crops are presented in table 2. On the average, the relative yield was calculated to within 8 percent or less of the measured yield.

A further test of the model comes in comparing computed with measured lettuce yields from an experiment conducted in Israel by David Russo (personal communication). This comparison provides a rigorous test for the model because a wide range of water application rates and water salinities were used in the experiment; lettuce is a salt-sensitive crop where considerable variation in yield due to EC_i can be expected. The comparison represents a transfer of input data for the model from experiments conducted at Riverside to field experiments conducted in Israel. Small lettuce plants were transplanted to the field and treatment variables were immediately imposed. The crop was harvested at three different times with the final harvest being approximately 75 days after transplanting. Measured and predicted lettuce yields as affected by quantity and quality of irrigation water are presented

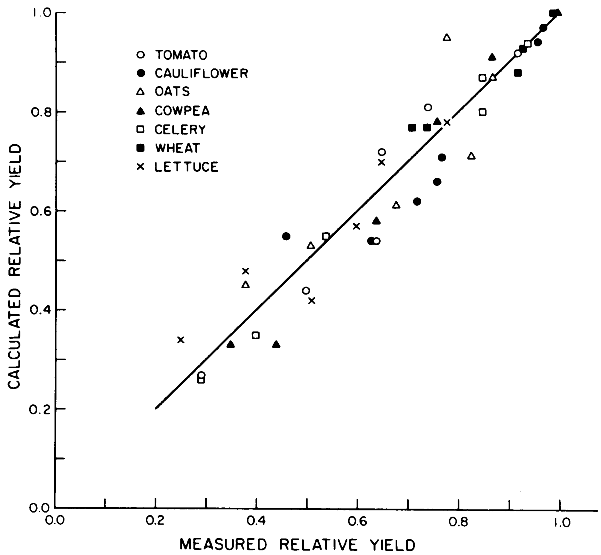

Fig. 21. Comparison between calculated and measured relative yields for several crops.

TABLE 2. CORRELATION COEFFICIENT AND AVERAGE DIFFERENCE BETWEEN CALCULATED AND MEASURED RELATIVE YIELD OF VARIOUS CROPS

Crop	Correlation coefficient	Average difference*
Cauliflower	.92	.06
Celery	.99	.03
Cowpea	.99	.04
Lettuce	.92	.06
Oats	.85	.08
Tomato	.97	.05
Wheat	.97	.02

*Average difference for the crop receiving various quantities of applied water.

in table 3. Except for the lowest application of water at EC_i = 1.72 dS/m, there was good agreement between measured and calculated relative yield for all values of applied water and EC_i.

An experiment was conducted investigating the effects of irrigation and salinity on corn production at Logan, Utah (Hanks et al. 1978). Soils were "presalinized" by adding approximately 30 cm of irrigation water having EC of 0.3, 2, 4, 6, 8, and 10 dS/m, which were designated as treatments S0, S1, S2, S3, S4, and S5, respectively. The crop was irrigated with a line-source sprinkler irrigation system to impose variable water application rates. Irrigation water qualities were EC of 0.3 (WQ0) and EC of 2.0 (WQ2) dS/m. Approximately 8 cm of precipitation occurred during the season, and seasonal E_p was 70 cm.

The present model was developed using relationships that are strictly valid only for steady state conditions; the experimental conditions (Hanks et al. 1978) were far from being

TABLE 3. MEASURED* AND PREDICTED RELATIVE LETTUCE YIELD AS AFFECTED BY QUANTITY AND QUALITY OF IRRIGATION WATER

EC_i	AW/E_p	Avg. yield	Meas. RY	Calc. RY	Difference
(dS/m)		(Mg/ha)			
1.72	0.37	23.80	.46	.20	.26
1.72	0.54	32.82	.63	.69	.06
1.72	0.86	44.59	.85	.94	.09
1.72	1.30	52.19	1.00	1.00	.00
3.10	0.61	28.41	.54	.62	.08
3.10	0.85	37.52	.72	.78	.06
3.10	1.08	43.61	.84	.84	.00
3.10	1.60	48.71	.93	.90	.03
4.71	0.70	25.80	.49	.54	.05
4.71	1.44	38.40	.74	.75	.01
4.71	1.78	41.40	.79	.78	.01
4.71	2.40	39.00	.74	.80	.06

*Data of David Russo (personal communication) from an experiment conducted in Israel.

steady state. Nevertheless, a comparison was made between predicted and measured yields for a weighted average EC_i ($\overline{EC}_i$) to test the utility of the model for nonsteady state conditions. Analyses were only conducted on treatments providing irrigation at each stage of growth.

Values for AW and EC_i ($\overline{EC}_i$ in this case) are required for equations (8) and (10). These values were determined using two sets of assumptions. In the first case, $\overline{EC}_i$ was calculated by

$$(\overline{EC}_i)_{sx} = \frac{30(EC)_{sx} + 0.3(I)}{30 + 8 + I} \qquad (14)$$

where sx represents the presalinization treatment, X, and I is the amount of irrigation (cm) after planting. The values of 30 and 8 represent the preirrigation and precipitation quantities, respectively. The EC of the postplant irrigation water was 0.3 dS/m. The associated AW values were the summations of precipitation, postplant irrigation and soil-water depletion. In the second case, only one-half (15 cm) of the preirrigation water was assumed to remain in the rooting zone and be effective. Thus, $\overline{EC}_i$ was calculated by using 15 instead of 30 in equation (14). The associated values of AW were summations of precipitation, postplant irrigation, and 15 cm of effective preplant irrigation.

A detailed comparison between measured and calculated RY values for the various treatments is presented in table 4. The first set of assumptions provides the better overall agreement between measured and calculated RY although both sets of assumptions provide about the same agreement for the intermediate salinity treatments (table 4). The relationship between measured and calculated RY for the first set of assumptions used in determining $\overline{EC}_i$ and AW is presented in figure 22. Poorest agreement between measured and calculated RY is for the nonsaline treatment. The measured RY for the nonsaline treatment was considerably lower than measured for some of the saline treatments at lower water application rates; thus appears to be unreasonable and could account for the poor prediction. Hanks et al. (1978) state that "there was considerable field variability." Considering the field

TABLE 4. MEASURED* AND PREDICTED RELATIVE CORN YIELDS AS AFFECTED BY IRRIGATION AND SALINITY UNDER TWO SETS OF ASSUMPTIONS ON $\overline{EC}_i$ AND AW.

		Measured		Calc. (assumpt. 1)				Calc. (assumpt. 2)			
Treatment	Irrig.	Grain yield	RY	AW	EC_i	RY	ΔRY	AW	EC_i	RY	ΔRY
	(cm)	(Mg/ha)		(cm)	(dS/m)			(cm)	(dS/m)		
S0 WQ0	6	2.6	.34	33	0.3	.69	.35	29	0.3	.58	.24
	17	4.8	.63	44	0.3	.96	.33	40	0.3	.86	.23
	25	6.6	.87	52	0.3	1.0	.13	48	0.3	1.0	.13
	31	7.6	1.00	59	0.3	1.0	0.0	54	0.3	1.0	0.0
	32	7.4	.97	59	0.3	1.0	.03	55	0.3	1.0	.03
Avg.							.17				.13
S0 WQ2	7	4.6	.60	32	0.5	.65	.05	30	0.5	0.5	0.0
	17	6.3	.82	46	0.8	.93	.11	40	0.8	0.8	.02
	27	7.2	.95	53	1.0	.97	.02	50	1.0	1.0	0.0
	34	7.2	.95	55	1.1	.98	.03	57	1.1	1.1	.05
	42	6.8	.89	65	1.2	1.0	.11	65	1.2	1.2	.11
Avg.							.06				.04
S1 WQ0	6	4.6	.60	32	1.4	.57	.03	29	1.1	1.1	.07
	17	6.2	.81	41	1.2	.78	.03	40	0.9	0.9	.02
	25	6.6	.87	51	1.0	.96	.09	48	0.8	0.8	.11
	31	7.4	.97	60	1.0	1.0	.03	54	0.7	0.7	.03
	32	7.1	.93	71	0.9	1.0	.07	55	0.5	0.5	.07
Avg.							.05				.06
S2 WQ0	6	3.8	.50	30	2.8	.45	.05	29	2.1	2.1	.03
	17	5.8	.76	42	2.3	.71	.05	40	1.6	1.6	.03
	25	6.2	.81	53	2.0	.87	.06	50	1.4	1.4	.09
	31	7.5	.99	59	1.8	.93	.06	57	1.2	1.2	.01
	32	7.0	.92	65	1.6	.98	.06	65	1.1	1.1	.08
Avg.							.06				.05
S3 WQ0	6	3.0	.39	34	4.1	.46	.07	29	3.2	3.2	.02
	17	5.5	.72	43	3.4	.63	.09	40	2.4	2.4	.06
	25	5.8	.76	52	2.9	.78	.02	50	2.0	2.0	.08
	31	7.1	.93	56	2.6	.83	.10	57	1.7	1.7	.05
	32	6.7	.88	61	2.4	.88	0.0	65	1.5	1.5	.11
Avg.							.06				.06
S4 WQ0	6	2.2	.29	30	5.5	.34	.05	29	4.2	.37	.08
	17	3.9	.51	37	4.4	.48	.03	40	3.1	.62	.11
	25	3.4	.45	42	3.8	.61	.16	50	2.6	.79	.34
	31	5.6	.74	45	3.6	.67	.07	57	2.3	.86	.12
	32	5.6	.74	45	3.3	.69	.05	65	2.0	.94	.20
Avg.							.07				.17
S5 WQ0	6	2.1	.28	22	6.8	.19	.09	29	5.2	.33	.05
	17	3.4	.44	34	5.5	.32	.12	40	3.9	.57	.13
	25	3.6	.47	42	4.9	.54	.07	48	3.3	.71	.24
	31	4.2	.55	48	4.5	.63	.08	54	3.0	.78	.23
	32	3.8	.50	49	4.4	.64	.14	55	2.9	.80	.30
Avg.							.10				.19

*Hanks et al. (1978).

(continued)

TABLE 4. CONTINUED

Treatment	Irrig.	Measured Grain yield	Measured RY	Calc. (assumpt. 1) AW	Calc. (assumpt. 1) EC_i	Calc. (assumpt. 1) RY	Calc. (assumpt. 1) ΔRY	Calc. (assumpt. 2) AW	Calc. (assumpt. 2) EC_i	Calc. (assumpt. 2) RY	Calc. (assumpt. 2) ΔRY
	(cm)	(Mg/ha)		(cm)	(dS/m)			(cm)	(dS/m)		
S5 WQ2	7	1.0	.13	22	7.0	.18	.05	30	5.5	.34	.21
	17	3.0	.39	32	6.1	.34	.05	40	4.9	.51	.12
	27	3.4	.45	42	5.4	.51	.06	50	4.1	.67	.22
	34	3.6	.47	49	5.1	.60	.13	57	3.8	.74	.27
	42	3.6	.47	57	4.8	.67	.20	65	3.6	.79	.32
Avg.							.10				.23

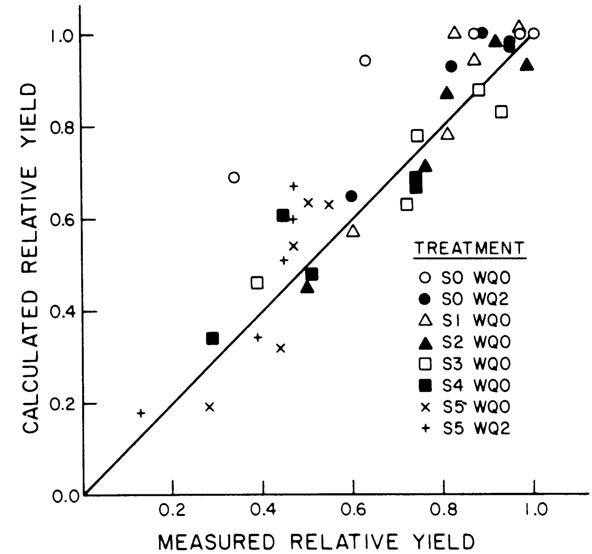

Fig. 22. Comparison between calculated and measured relative corn yields for various experimental treatments applied by Hanks et al. (1978).

variability in measured values, there is quite good agreement between model predictions and experimental observations.

These results suggest that use of a weighted average EC_i value in the model for nonsteady state conditions is appropriate and provides reasonable estimates of RY. Agreement between measured and calculated yields under these circumstances is the consequence of the apparent ability of the plant to integrate root-zone salinity over a growing season rather than the intrinsic nature of the model to accommodate nonsteady state conditions.

In summary, the number of experiments which have been conducted with water application quantity and quality variables is limited. Nevertheless, for those conditions where comparisons between measured and calculated yields can be made, there is reasonable agreement between the two values, providing some assurance of the utility of the model under field conditions.

UTILITY AND LIMITATIONS OF THE MODEL

Crop-water production functions for irrigating with saline waters are required for the development of optimum irrigation management strategies. The model presented here can be used to synthesize these production functions. One can use the model directly, using equations (8) and (10), with appropriate input data, such as contained in table 1, to compute production functions for any set of conditions. Production functions for several crops have been computed and graphically illustrated in this report for the convenience of those who do not have appropriate computer facilities. Furthermore, functional relationships between relative yield and quantities and qualities of applied irrigation water are provided for each crop. Some accuracy is lost in using the functional relationships rather than direct computations from equations (8) and (10). For example, the quadratic relationship indicates a yield decrease at very high values of AW/E_p. Also the quadratic relationship tends to underestimate relative yield at intermediate values of AW/E_p, particularly when maximum yields are achieved at fairly low AW/E_p values. Note that the lowest r^2 occur for the lowest values of EC_i (Appendix A).

The functional relationship between leaching fraction or deep percolation and quantity and quality of applied water is provided in Appendix B for the various crops analyzed. Functional relationships between the EC of the drainage water can be computed from the functional relationships presented for the leaching fraction.

The computed production functions are valid within the range of conditions that were assumed in developing the model. A first condition for the model validity is a linear relationship between yield and ET. This factor has been quite well established from experimental data for many crops and is not expected to be a major limitation in the model utility. This condition, however, was not met for barley and sorghum (Hoffman and Jobes 1983 Hoffman et al. 1979); therefore, production functions have not been reported for these crops in this report. Even though the linear relationship between yield and ET is generally valid, the specific relationship may vary with location and irrigation system. In reality, one would expect the yield to be directly related to transpiration, but evaporation and transpiration are rarely, if ever, separately measured in experiments. Applied water has been scaled by pan evaporation to facilitate transfer of the production functions to various geographic areas. Errors associated with transferring production functions between geographic areas, however, is recognized.

Use of coefficients as proposed by Maas and Hoffman (1977) as an index of crop sensitivity to salinity is another significant component of the model. Bresler, McNeal, and Carter (1982, p. 203) suggest that Maas and Hoffman type coefficients are valid only for cases of high relative amounts of water. Comparison of experimental and computed yields in the preceding section do not support this restricted interpretation on the validity of the Maas-Hoffman coefficients. Agreement between calculated and measured yields do not differ over the entire range of water application. Indeed, the curves presented by Bresler, McNeal, and Carter (1982, p. 203) from which they drew their suggestion relative to the Maas-Hoffman coefficients are questionable. Their curves indicate that a ratio of water application to ET of about 1.5 must be applied to obtain maximum yield even when the soil is nonsaline. Indeed, an unreasonable relative yield of less than 0.8 is predicted for a nonsaline condition when the amount of applied water equals evapotranspiration.

The crop-sensitivity coefficients are assumed to be applicable to all stages of growth. Some crops may be more sensitive during seedling stage than after the plants are well established (Meiri 1984). Most coefficients reported by Maas and Hoffman were derived from experimental conditions of establishing the plants before imposing the salinity treatments. Thus, the production functions are probably most applicable for conditions where plant establishment is not jeopardized by soil salinity. In other words, the production functions may not be appropriate for conditions of initial high soil salinity, leading to poor plant establishment.

The production function is on the basis of seasonal-applied water which must include preplant irrigation and/or precipitation used by the crop. The model was developed for constant values for EC_i and its appropriateness for the condition where considerable amounts of precipitation (or irrigation water of lower EC) is questionable. There is, however, experimental evidence (Meiri 1984; Shalhevet 1984) that plants respond to the weighted average of the EC of various waters applied during the season. This is further supported by the agreement with experimental data when the weighted average EC of waters was used in the computations (table 4). Thus, the production functions as presented may be appropriate when the EC_i value represents the weighted average EC_i.

In developing the model, it was assumed that application of nonsaline water above ET_{max} resulted in a yield plateau. In other words, no detrimental effects from excess water, such as waterlogging, are assumed. Clearly, there is an upper limit (dependent on soil properties) that water can be applied without causing poor aeration. The upper limit must be established for individual soils and can not be generalized. However, when the optimal water-management solution calls for very large water applications, consideration must be given as to whether the given soil can accommodate those high volumes of water without detrimental crop effects.

A third component of the model development was the relationship between EC_i and the resultant average root-zone salinity. The relationship was originally developed by Raats (1974) under conditions of steady water flow and steady state soil salinity development. Conceptually, there is, therefore, a question as to whether the model would be applicable for the intermittent water-flow conditions common in irrigated agriculture. The good agreement between model prediction and plant growth of tall fescue under different irrigation frequencies suggests that the applicability of the model is not restricted to high-frequency irrigation.

In summary, a number of assumptions went into the model development which could be restrictive in utilizing the model under field conditions. To the extent that model predictions could be compared with experimental data, it appears that the assumptions are not overly restrictive. On the other hand, experimental tests have not been conducted on a sufficiently wide range of conditions to be completely assured of the range of validity of the proposed production functions.

Because there is some uncertainty about the range of validity of the proposed production functions, what are the alternatives? One alternative is field experimentation which is expensive, particularly if several combinations of water application and EC_i variables are included. Furthermore, geographic transferability of the experimental data has the same problem as transferring model predictions between geographic areas.

Another alternative is to use a model for nonsteady flow, nonuniform soil and water salinity, and variable applications of irrigation and rain, such as outlined by Hanks (1984). The problem with this approach is that the input data requirements in using the model are formidable. The following are examples of information which were stated as being required (Hanks 1984). Hydraulic conductivity and soil matric potential must be known as functions of volumetric soil-water content. Data are needed to compute the value for a root-extraction term. The root-density function in a particular depth increment of soil is necessary as well as values of the root-water potential at wilting. Initial conditions, including the value of water content and soil solution concentration vs. depth at the beginning of the season, must be known. The boundary conditions, which must be specified, include potential climatic conditions at the soil-plant surface for the entire time of simulation, the potential evaporation and transpiration as a function of time as well as irrigation, and the rainfall amounts and time increments required. Information about the lower boundary in the soil is necessary.

Conceptually transient state models should provide better predictions than the model presented in this report. However, the difficulty and uncertainty of obtaining appropriate input parameters may ultimately lead to predictions which are poorer than those that can be obtained from a conceptually inferior model.

The production functions as presented in this paper are for uniform water application. In the case of nonuniformity, which is typical of agricultural field crops, the ultimate relationship between average applied water and yield can be significantly different from those presented in this paper (Childs and Hanks 1975; Feinerman, Knapp, and Letey 1984). The production functions reported in this paper can be combined with water application distribution by the technique proposed by Letey, Vaux, and Feinerman (1984) to compute production functions for the combined effects of salinity and nonuniformity of irrigation. The results will be different from those presented by Feinerman, Knapp, and Letey (1984) because the latter assumed that steady state yields are zero when water applications are less than ET_{max}. That analysis did not allow for ET adjustment to salinity which allows leaching even for low-water applications.

APPENDIX A

COEFFICIENTS AND r^2 FOR THE FUNCTIONAL RELATIONSHIP BETWEEN RY AND AW/E_p FOR VARIOUS CROPS AND GIVEN VALUES OF EC_i.

$$RY = a + b(AW/E_p) + c(AW/E_p)^2$$

EC_i	a	b	c	r^2
Alfalfa				
1	−.107	1.88	−.771	.989
2	−.086	1.66	−.629	.995
3	−.067	1.49	−.537	.995
4	−.064	1.39	−.497	.996
6	−.055	1.22	−.430	.996
8	−.047	1.07	−.372	.996
Cauliflower				
0.5	−.628	2.77	−1.121	.975
1	−.886	3.34	−1.434	.983
2	−.614	2.50	−.943	.995
3	−.577	2.24	−.793	.993
4	−.520	2.01	−.695	.994
6	−.429	1.64	−.542	.997
8	−.384	1.40	−.457	.997
Celery				
0.5	−1.461	4.38	−1.904	.986
1	−1.468	4.30	−1.859	.993
2	−1.329	3.76	−1.526	.994
3	−1.138	3.25	−1.284	.996
4	−1.046	2.96	−1.144	.996
6	−.914	2.50	−.932	.996
8	−.893	2.31	−.856	.996
Corn				
1	−.230	2.36	−1.077	.984
2	−.194	2.01	−.839	.994
3	−.170	1.77	−.715	.994
4	−.160	1.60	−.640	.994
6	−.138	1.30	−.508	.994
Cotton (plateau)				
1	−.002	2.34	−1.207	.841
2	−.012	2.26	−1.114	.849
3	−.054	2.32	−1.139	.868
4	−.137	2.56	−1.297	.902
6	−.159	2.41	−1.145	.919
8	−.181	2.33	−1.083	.943
11	−.215	2.18	−.961	.962
Cowpea				
1	−1.223	4.04	−1.758	.956
2	−1.372	4.25	−1.852	.982
3	−1.330	3.97	−1.658	.993
4	−1.206	3.48	−1.363	.997
6	−.890	2.47	−.830	.997
8	−.764	2.02	−.654	.997
11	−.644	1.50	−.455	.996

(continued)

APPENDIX A *(continued)*

$RY = a + b(AW/E_p) + c(AW/E_p)^2$

EC_i	a	b	c	r^2
Lettuce				
0.5	−.586	3.14	−1.427	.823
1	−.286	2.44	−1.074	.804
2	−.236	1.94	−.751	.903
3	−.549	2.33	−.912	.946
4	−.511	2.05	−.780	.965
6	−.424	1.54	−.547	.972
Oats (grain)				
1	−.162	1.76	−.621	.974
2	−.156	1.66	−.572	.987
3	−.149	1.52	−.493	.987
4	−.141	1.42	−.465	.988
6	−.118	1.26	−.396	.987
8	−.117	1.15	−.353	.988
11	−.118	1.00	−.301	.988
Sugarbeets (roots)				
1	−.455	2.60	−1.088	.928
2	−.252	2.21	−.912	.929
3	−.282	2.16	−.871	.904
4	−.135	1.80	−.688	.891
6	−.498	.66	−.225	.951
8	−.498	.60	−.196	.968
11	−.443	.61	−.194	.987
Tomato				
1	−1.661	5.08	−2.361	.983
2	−1.462	4.33	−1.883	.995
3	−1.315	3.76	−1.557	.994
4	−1.201	3.36	−1.359	.995
6	−1.013	2.69	−1.042	.997
8	−.903	2.23	−.830	.997
Wheat				
1	not enough variance to establish estimations			
2	−.655	.590	−.241	.553
3	−.507	.870	−.368	.682
4	−.448	.933	−.378	.786
6	−.501	.779	−.297	.951
8	−.467	.745	−.262	.977
11	−.484	.621	−.203	.992

APPENDIX B

COEFFICIENTS AND r^2 FOR THE FUNCTIONAL RELATIONSHIP BETWEEN LEACHING FRACTION (L) AND DEEP PERCOLATION (DP) TO AW/E_p AND EC_i FOR VARIOUS CROPS.

$$L = a + b(AW/E_p) + c(AW/E_p)^2 + d(EC_i) + e(EC_i)^2 + f(AW/E_p)(EC_i)$$

$$DP = a\,AW + b\,AW^2/E_p + c\,AW^3/E_p^2 + d(AW)(EC_i) + e(AW)(EC_i)^2 + f(AW)^2(EC_i)/E_p$$

Crop	a	b	c	d	e	f	r^2
Alfalfa	0.002	−0.055	0.251	0.070	0.0009	0.027	.970
Cauliflower	−0.036	0.116	0.158	0.053	0.0001	−0.023	.966
Celery	−0.006	−0.180	0.332	0.044	0.0*	−0.014	.975
Corn	−0.069	0.189	0.179	0.087	−0.0005	0.043	.966
Cotton	−0.128	0.462	0.072	0.031	0.0007	−0.027	.957
Cowpea	−0.115	0.112	0.201	0.039	0.0006	−0.023	.967
Lettuce	−0.382	1.051	−0.243	0.054	0.0005	−0.033	.985
Oats	−0.088	0.215	0.066	0.048	−0.0003	−0.015	.968
Sugarbeet	−0.235	0.509	0.002	0.012	0.0003	−0.009	.967
Tomato	−0.115	0.095	0.237	0.046	0.0*	−0.021	.976
Wheat	−0.525	1.098	−0.240	0.008	0.0006	0.009	.981

*Not significantly different from zero.

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Issued in furtherance of Cooperative Extension work, Acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture. Jerome B. Siebert, Director of Cooperative Extension, University of California.

2.5m-pr-2/86-HS/VG

The Journal HILGARDIA is published irregularly. Number of pages and number of issues vary per annually numbered volume. Address: Agriculture and Natural Resources Publications, University of California, Berkeley, CA 94720.