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# Environmental Implications of Adopting a Dominant Factor Approach to Salinity Management

Uri Shani, Alon Ben-Gal,* and Lynn M. Dudley


## ABSTRACT

**Additive or multiplicative models of crop response on which salinity management theory have been developed may lead to an erroneous perception regarding compensative interaction among salinity and other growth factors. We present results from studies of biomass production and transpiration of corn (*Zea mays* L. cv. Jubilee), melon (*Cucumis melo* L. subsp. *melo* cv. Galia), tomato (*Lycopersicon esculentum* Mill. cv. 5656), onion (*Allium cepa* L. cv. HA 944), and date palms (*Phoenix dactylifera* L. cv. Medjool) under salinity combined with water or nitrate (growth promoters) or with boron (growth inhibitor). The measured crop responses were to the more severe stress rather than to combinations of the individual effects of the various stresses. Consequences of shifting management of saline water to a dominant factor approach include reduction of environmental contamination and conservation of water resources.**


In irrigated agriculture, ions concentrate as applied water evaporates from the soil surface or is transpired by plants. Accumulation of salt in the root zone decreases agricultural productivity and where drainage is inadequate, excess irrigation, designed to remove accumulated salts from the root zone, often leads to waterlogging and further salinization. According to the FAO (2002) some 20 to 30 million hectares of irrigated land are currently seriously damaged by salinity and 0.25 to 0.5 million hectares are lost from production every year as a result of salt accumulation. As of 1990, 1.4 million hectares of irrigated land in California had a water table within 1.5 m of the surface and 1.7 million hectares were saline or sodic (Tanji, 1990). The Australian National Land and Water Resources Audit (2001) has identified approximately 8.8 million hectares in Western Australia at high risk of developing shallow saline water tables by the year 2050. Although reduced in recent years through extensive drainage and ground water management, some 25% (more than 5 million hectares) of the Indus River basin of Pakistan are still estimated to be effected by salinity and waterlogging (Tanji and Kielen, 2002).

Plant growth involves multifaceted, interconnected biological and physical factors and is determined by not only osmotic stress and specific-ion toxicity, but also by changes in soil-water availability via feedback mechanisms with soil water content and hydraulic conductivity. For example, plant stress is aggravated due to increased salinity following root water uptake and the resulting decrease in soil water content. Integration of physiological responses in plants from subcellular mechanisms involving specific ions to whole-plant level is currently not feasible and quantitative description therefore relies on understanding and analysis of whole-plant and field-scale response.

Experimental evaluation of the nature of multiple environmental growth promoters and inhibitors on plant performance is extremely difficult due to the levels of precision and extent of a database needed to describe complex nonlinear relationships. In fact, before recent advances in electronic automation and control, such experiments were unfeasible and, to date, only few reports of precise, controlled experiments involving multiple factors on plants are available (Russo and Bakker, 1987; Shani and Dudley, 2001; Ben-Gal and Shani, 2002). Consequently, salinity management theory has been derived from blending thermodynamic and semi-empirical considerations (Childs and Hanks, 1975; Kafkafi, 1984; Bresler, 1987; van Genuchten, 1987; Cardon and Letey, 1992; Shani and Hanks, 1993; Homaee et al., 2002) with nominal, possibly unsatisfactory, support by experimental evidence. Crop and water management under combined salinity and water availability was based on the notion that water flow rate to plants responds to gradients in total water potential (the sum of osmotic and matric components) in the soil–plant–atmosphere continuum, referred to as potential-flow theory by Zhang and Elliot (1996). Hypothesized competition between chloride and nitrate has led to theory implying that additional nitrate can offset increases in salinity (Kafkafi, 1984). Likewise, enhanced yield decrease has been assumed where salinity occurs simultaneously with a toxic ion such as boron (Shani and Hanks, 1993).

Simulated results of plant response to multiple factors based on the above theories have suggested that where two factors are applied simultaneously they affect the plant in an additive manner. These approaches further suggest that improvements in one factor could compensate for another factor's deficiency or toxicity. Compensative interactions are not unique to these additive models and result from other assumptions regarding interrelationships between growth factors as well. The Mitscherlich–Baule (Stewart, 1932) multiplicative approach, applied by Wallace (1990) for multiple nutrient interactions and by Shenker et al. (2003) for combined salt and nitrogen, exhibits compensation. Homaee et al.

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**Abbreviations:** EC, electrical conductivity; *T*, transpiration; *Y*, yield; $\pi$, osmotic potential; $\psi$, matric potential.

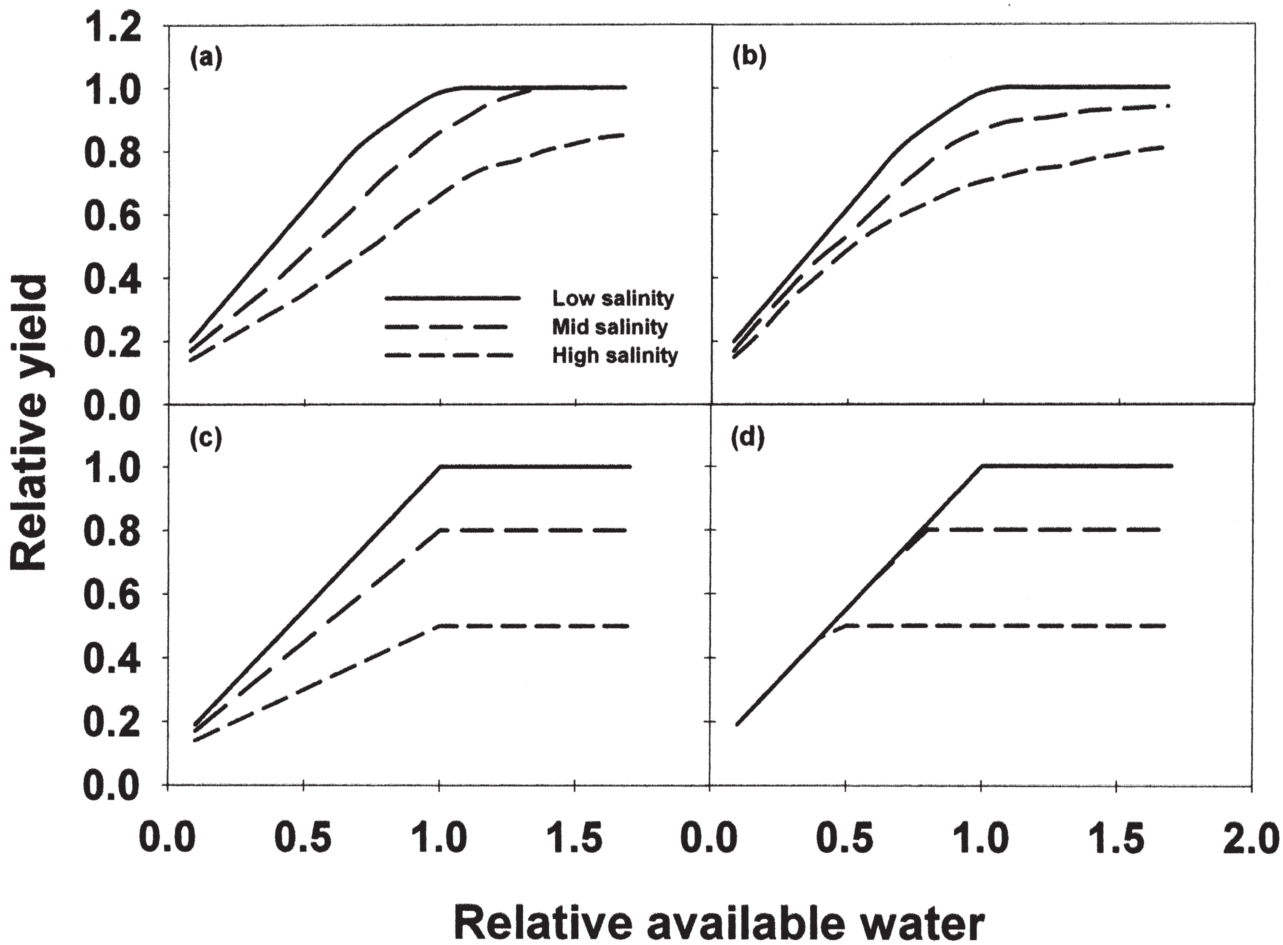


**Fig. 1. Schematic illustration of yield response to combined water availability and salinity according to four approaches: (a) additive–compensative, (b) multiplicative–compensative, (c) multiplied piecewise linear relationships, and (d) dominant factor.**

(2002) and Dudley and Shani (2003) both presented multiplicative relationships between salinity and available water where compensation is evident as well.

We suggest that, at the plant-scale to field-scale, the time-integrated response to multiple environmental growth factors and stresses is determined by a dominant factor. The dominant factor approach is an expansion of the Liebig–Sprengel "law of the minimum" (van der Ploeg, 1999) to include salinity and water stresses as applied by Shani and Dudley (2001) and salinity and boron from Ben-Gal and Shani (2003). We examined data from a series of experiments where we have studied the response of a variety of crops to multiple environmental growth factors under different soils and climates. Specifically, we investigated whether plant responses to the combined environmental factors salinity–water, salinity–nitrate (growth inhibitor–promoter pairs), or salinity–boron (growth inhibitor–inhibitor pair) to a limiting factor or to some combined effect of both paired factors. While the Liebig–Sprengel law of the minimum assumes linear response functions, the dominant factor approach can include factor-specific response functions of various natures.

A schematic illustration of interactions discussed above between factors on plants is depicted in Fig. 1. Relative yield ($Y_r$) as a function of various assumed salt ($\pi$ = osmotic potential [L]) and water ($\psi$ = matric potential [L]) interrelationships is shown for an additive (hence compensative) approach (Fig. 1a) following the uptake model of van Genuchten (1987):

$$Y_r = \frac{1}{1 + [(a_1\Psi + a_2\pi)/h_{50}]^p} \qquad [1]$$

where $h_{50}$ (L) is the total soil-water potential causing 50% yield decrease and $a_1$, $a_2$, and $p$ are plant specific empirical coefficients. A potential flow model (Fig. 1b) was presented by Dudley and Shani (2003):

$$Y_r = K(\Psi)(H_{root}) \times \frac{1}{1 + \left(\frac{\pi}{\pi_{50}}\right)^p} \times T_p \qquad [2]$$

where $K$ (L T$^{-1}$) is the hydraulic conductivity, $H_{root}$ is the root water head, $\pi_{50}$ (L) is osmotic potential causing 50% yield decrease, and $T_p$ (L T$^{-1}$) is potential transpiration. Multiplied piece-wise linear relationships (Fig. 1c) as presented by Homaee et al. (2002) are shown in Eq. [3]:

$$Y_r = \frac{\Psi - \Psi_0}{\Psi_1 - \Psi_0} \times [1 - \alpha(\pi_{cr} - \pi)] \qquad [3]$$

where the reduction function of Feddes et al. (1978) for matric potential was applied together with a piecewise linear function for reduction due to salinity from Maas and Hoffman (1977). Threshold value for response to salinity is $\pi_{cr}$, $a$ is slope of the salinity response curve, $\psi_0$ is matric potential causing plant death, and $\psi_1$ is threshold value for matric potential effects. A linear example of the dominant factor approach (Fig. 1d) is shown in Eq. [4]:

$$Y_r = \min\begin{cases}\begin{cases}1; & \pi \geq \pi_{cr}\\ 1-\alpha(\pi-\pi_{cr}); & \pi < \pi_{cr}\end{cases}\\ \begin{cases}1; & \psi \geq \psi_1\\ \dfrac{\Psi-\Psi_0}{\Psi_1-\Psi_0}; & \psi < \psi_1\end{cases}\end{cases} \quad [4]$$

## MATERIALS AND METHODS

Our investigation includes the summary of experimental data from published investigations including the response of melon (*Cucumis melo* subsp. *melo* cv. Galia) and corn (*Zea mays* L. cv. Jubilee) to deficit irrigation and to salinity under field conditions and in different climates and soils (Study 1); the response of tomato (*Lycopersicon esculentum* Mill. cv. 5656) and date palms (*Phoenix dactylifera* L. cv. Medjool) to salinity and to excess boron levels in lysimeters in the field and in greenhouses (Study 2); and corn (cv. Jubilee) and onion (*Allium cepa* L. cv. HA 944) response to salinity and to N level in field and greenhouse lysimeters (Study 3). All factors ranged from levels not limiting to plant function to severe inhibition.

Experimental procedures included measuring the water and solute balance over the irrigation season, and determination of evapotranspiration, growth, and yield of each crop. Full protocols and details of experimental design have been previously published (Shani and Dudley, 2001; Ben-Gal and Shani, 2002; Tripler, 2004; Shenker et al., 2003). For Study 1, corn and melon were grown in field experiments (Shani and Dudley, 2001) under six irrigation ($I$) levels. Irrigation levels given as a fraction of potential evapotranspiration ($E_0$), determined from a Class A evaporation pan, were $I$ = 0.2, 0.4, 0.7, 1.0, 1.3, and 1.7. The plots were irrigated with waters of electrical conductivity (EC) = 3, 6, and 9 dS m$^{-1}$ with salinity composed of $CaCl_2$ and NaCl salts at a Ca to Na molar ratio of 2.0. For Study 2, tomatoes and dates were grown in lysimeters under combined conditions of varying salinity and B levels (Ben-Gal and Shani, 2002; Tripler, 2004). Tomatoes were irrigated with waters of EC = 1, 3, 6, and 9 dS m$^{-1}$ in combination with B concentrations of 0.028, 0.185, 0.37, 0.74, 1.11, and 1.48 mol m$^{-3}$. Salinity treatments were created by adding NaCl and $CaCl_2$ at a 1:1 molar ratio while B was added to the irrigation water as boric acid. Dates were irrigated with water of EC = 1, 4, 8, and 12 dS m$^{-1}$ combined with B concentrations of 0.03, 0.19, 0.46, 1.85, and 3.7 mol m$^{-3}$. Salinity levels were a result of adding NaCl and $CaCl_2$ at a 3:1 molar ratio and B was added to irrigation waters as boric acid. For Study 3, corn and onion were grown in lysimeters under conditions of salinity combined with variable nitrogen fertilization levels (Shenker et al., 2003). Salinity levels of irrigation waters for corn were EC = 0.5, 2.5, 5, and 7.5 dS m$^{-1}$ and for onion irrigation water salinities were EC = 0.5, 2, 4, and 7 dS m$^{-1}$. Salinity treatments were created by adding NaCl and $CaCl_2$ to the irrigation water at 2:1 molar ratios. Nitrogen fertilizer was applied at rates that were percentages of the local recommended commercial level and varied with plant age. The application rates for corn were 0, 15, 45, 70, 100, and 150% while for onions they were 0, 35, 70, 100, and 120% For the experiments on annual crops, yield was determined as total aboveground, dry biomass. For date palms, yield was determined as the total area of the canopy cover. Yield data are presented as relative yield ($Y_r$) where $Y_r = Y/Y_{max}$, with $Y_{max}$ being the greatest yield measured over all treatments in a given experiment.

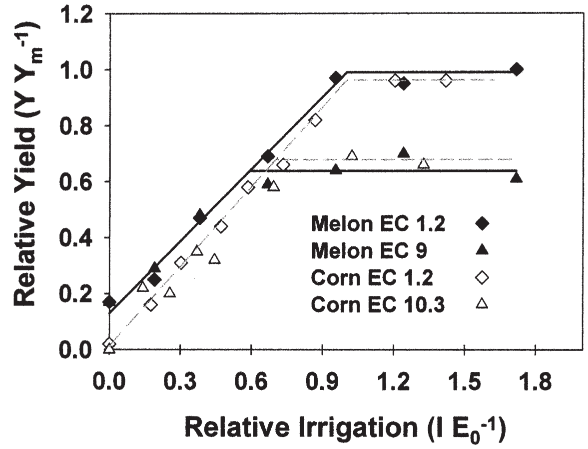


**Fig. 2. Yield ($Y$) response to combined salinity and water. Experimental (symbols) and computed (lines, assuming a dominant factor model) results for corn grown in field experiments in Logan, UT, and melons grown in field experiments in the Arava, Israel. Irrigation water quantity ($I$) is shown relative to potential evapotranspiration ($E_0$). The term $Y_m$ is maximum yield and EC is electrical conductivity.**

To test our hypothesis that growth is limited by a dominant factor, data were fit to a piecewise linear model. The response model follows the concept of the Liebig–Sprengel law (van der Ploeg, 1999):

$$Y_r = \min\{g_i(x_i)\}$$

where $Y_r = Y_i Y_m^{-1}$, $Y_m$ is a maximum yield obtained in each experiment, $x$ is an environmental factor ($i = 1...n$), and $g_i$ is the associated piecewise linear response function. The parameterization method for the model was given in previous work (Shani and Dudley, 2001). Parameters of the model were fitted to data reflecting situations in which only one of the factors (salinity, water, N, or B) determined yield, using the Ordinary Least Square model (Quantitative Micro Software, 1997). The combined effect of the two factors at all experimentally tested levels was evaluated against the model by a Wald test (Kennedy, 1992) under the null hypotheses that parameters describing the same property (e.g., slope, intercept) of the various salinity and other treatments were equal. Accuracy of prediction by the dominant factor, additive–compensative, and multiplicative–compensative models was compared using an $F$ test on deviations from measured values.

## RESULTS AND DISCUSSION

Plant response to the salinity–water combinations was to water alone at low irrigation levels. Yield for corn and melon increased linearly in response to irrigation until a maximum yield for each salinity treatment was reached (Fig. 2). The maximum yield decreased with increasing salinity. Similarly, responses of corn and onion to increases in nitrogen were linear and reached

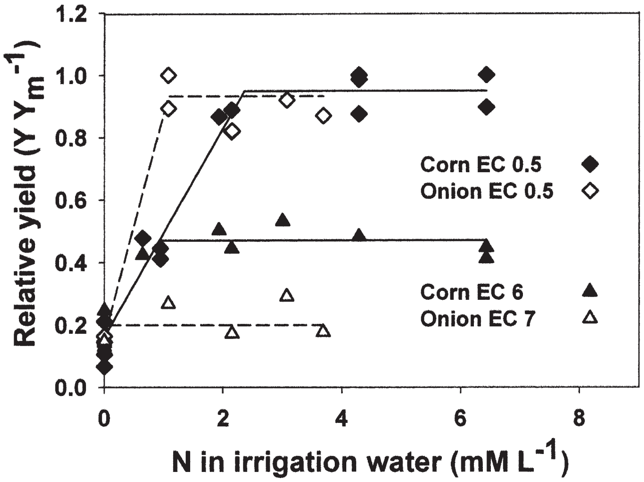


Fig. 3. Yield ($Y$) response to combined salinity and nitrogen. Experimental (symbols) and computed (lines, assuming a dominant factor model) results for corn grown in greenhouse lysimeters in the Arava and in Rechovot, Israel, and onion grown in lysimeters in the Arava, Israel. From Shenker et al. (2003). The term $Y_m$ is maximum yield, and EC is electrical conductivity.

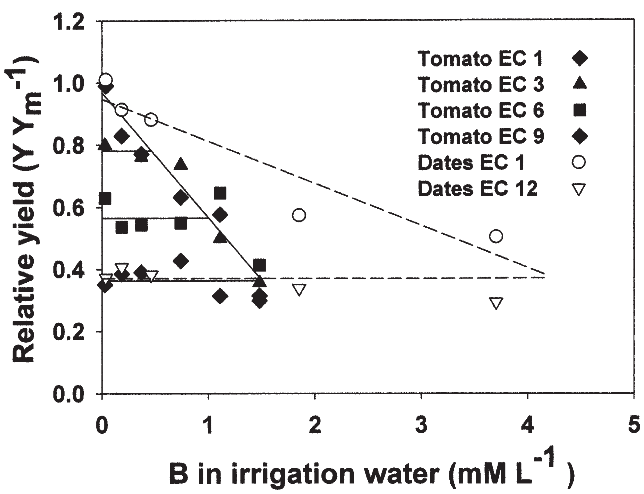


Fig. 4. Yield ($Y$) response to combined salinity and excess boron. Experimental (symbols) and computed (lines, assuming a dominant factor model) results for tomato grown in greenhouse lysimeters and date palm grown in field lysimeters in the Arava, Israel. From Ben-Gal and Shani (2002) and Tripler (2004). The term $Y_m$ is maximum yield, and EC is electrical conductivity.

maximum yields that depended on salinity (Fig. 3). Relative yield of tomato and date palm was reduced by excess boron in a linear fashion, with maximum yield and threshold B values determined by salinity (Fig. 4).

Yield response to water and salinity for the melon data according to the limiting model was compared to both additive–compensative (Eq. [1]) and multiplicative–compensative response models (Eq. [2], Fig. 5). Dudley and Shani (2003) compared additive versus multiplicative approaches and optimized each model parameters to best fit the data set. Analysis of prediction success of the three approaches revealed that the order of successful prediction was dominant factor > multiplicative > additive where the difference between the dominant and additive was significant at $\alpha = 0.003$ and the difference

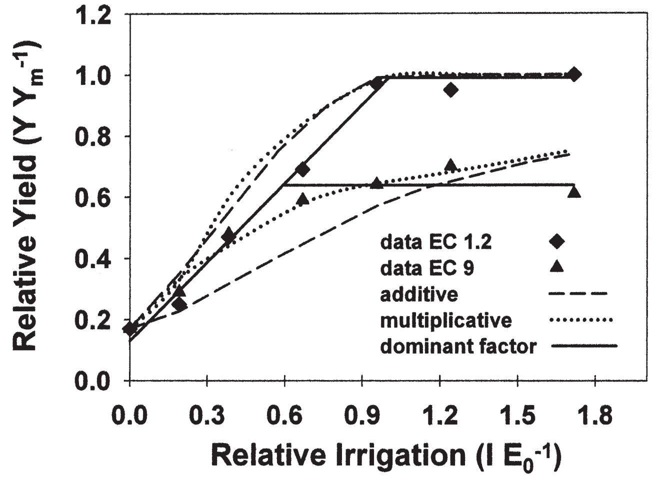


Fig. 5. Comparison of the additive–compensative and multiplicative–compensative models with the dominant factor model for the melon data from Shani and Dudley (2001). The additive and multiplicative model results were taken from Dudley and Shani (2003). Experimental (symbols) and computed (solid lines, assuming dominant factor model; dashed lines, assuming additive compensation; dotted lines, assuming multiplicative compensation) results. The term $I$ is irrigation quantity, $E_0$ is potential evapotranspiration, $Y$ is yield, $Y_m$ is maximum yield, and EC is electrical conductivity.

between dominant and multiplicative was significant at $\alpha = 0.07$. The additive model predicted a salinity response at low irrigation levels whereas measured data showed plant yield to respond to water with no compounding salinity effect at low irrigation. The multiplicative model predicted yields of the high salinity well, but overpredicted yields at lower than optimal water levels. Both of the compensating models predicted continued increases in yields with increased application of saline water.

For all the combinations of stress-causing factors and all the crops, neither additive nor multiplicative effects on plant yield and transpiration were observed (Fig. 2, 3, and 4). In fact, yield at each combination of the various factors was primarily controlled by a single factor, most limiting to plant growth. The piecewise linear approach highlights the level where response changes from one factor to the other. The model produces a response "envelope" that contains all possible yields. The diagonal lines represent response to $X_i$ alone and the lines parallel to the $x$ axis characterize response to salinity alone.

One of the potential environmental consequences of management by a compensative model versus a limiting model can be illustrated by simple calculation. The compensative curve in Fig. 5 indicates that melons require 1.1 m of 9 dS $m^{-1}$ water to achieve maximum yield, whereas the data show that maximum yield is achieved with application of only 0.6 m due to limitation of yield by salinity. Thus, the compensative model would increase water application by 0.5 m and salt loading by 20 000 kg $ha^{-1}$. The additional 0.5 m of water required by management by the compensative model would not be used by the crop and has the potential to raise ground water and exacerbate salinity problems.

Other environmental and resource management repercussions of changing the salinity management paradigm from a compensative to a limiting factor response are potentially significant. Figure 3 suggests that additional nitrate does not compensate for salinity. Counter to practice, lower N levels are required where saline water limits production. For example, the data for corn show that at an irrigation water salinity of 6 dS $m^{-1}$ addition of N beyond 25% of the commercial recommendation (1 m$M$ $L^{-1}$) failed to increase yield. Excess nitrates, designed to recompense salinity stress, simply contaminate the environment when salinity is the yield limiting factor. Water may both be saline and contain excess B; however, as demonstrated in Fig. 4, management should regard only the limiting constituent. At EC $\geq$ 9 dS $m^{-1}$, B is not consequential for poor quality water use on tomato. Consequences of such consideration include potential utilization of water sources currently thought to be inappropriate for irrigation.

## CONCLUSIONS

Quantitative description of the complex mechanisms contributing to the response of plants to combined growth factors requires response terms for individual variables affecting growth and attention to interaction among variables. We have shown that, at the plant and field scales, the complex interactions may be adequately represented by a dominant factor approach (Fig. 1–5; Shani and Dudley, 2001; Ben-Gal and Shani, 2002; Tripler, 2004; Shenker et al., 2003). While both the dominant factor approach and the currently accepted notions of compensative plant response to multiple stresses are simplifications of complex plant response, they generate different notions of system behavior and options for management.

The replacement of a compensative paradigm for interpreting multiple environmental growth factors with a limiting model may have important consequences for management of irrigated agriculture. Irrigation management based on a dominant factor approach realizes that manipulation of a nondominant factor cannot influence the yield. If, for example, salinity is limiting uptake and growth, water and nutrient needs are a function of the specific salinity level. Optimum irrigation water quantities and fertilizer application rates are therefore necessarily lower for conditions of higher salinity as compared to conditions of lower salinity. Excess water applied and not used by the plant most likely contributes to degradation of ground water resources and elevation of water tables. The dominant factor model both negates currently accepted notions concerning irrigation requirements under saline conditions and indicates that, when a particular factor such as salinity is responsible for less than optimal growth, inputs of other resources (i.e., fertilizers) should be reduced to prevent economic loss and environmental contamination.

Deficit irrigation with poor quality water is not a favorable combination for farmers. Equally unwelcome are crop growing environments where conditions of salinity are coupled with high levels of other toxic substances or deficient levels of nutrients. Nonetheless, a number of situations including drought, the need to dispose of drainage or other waste water, or limited water resources due to competition with urban or industrial consumers can induce at least temporary crop production under multiple stress conditions. The compensative models discourage utilization of poor quality water under deficit irrigation because yield loss is predicted for even small amounts of salinity. In addition, these models predict that more water is required than actually necessary to achieve maximum yield.

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