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Crop Response and Management of Salt-Affected Soils

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INTRODUCTION

Salinity is a major factor reducing plant growth and productivity throughout the world [1]. Approximately 10% of the world's 7×10^9 ha arable land surface consists of saline or sodic soils. The percentage of cultivated lands affected by salts is even greater. Of the 1.5×10^9 ha cultivated lands, 23% are considered saline and another 37% are sodic. Although the data are tenuous, it has been estimated that one-half of all irrigated lands (about 2.5×10^8 ha) are seriously affected by salinity or waterlogging [2]. Historically, soil salinity contributed to the decline of several ancient civilizations [3]. Despite the advanced management technologies available today, salinization of millions of hectares of land continues to reduce crop production severely in the United States and worldwide [4]. The National Academy of Sciences [5] includes salinization of soils and waters as one of the leading processes contributing to a worldwide biological catastrophe.

Sustained and profitable production of crops on salt-affected soils is possible if appropriate on-farm management decisions are made. To be successful, growers require an understanding of how plants respond to salinity, the relative tolerances of different crops and their sensitivity at different stages of growth, and how different soil and environmental conditions affect salt-stressed plants. This chapter discusses the effects of soil and water salinity on agronomic and horticultural crop plants, presents data on the tolerance of crops to salinity, and considers consequences of various cultural and management practices on crop yield responses.

PLANT RESPONSE TO THE SOIL ENVIRONMENT

Saline Soils

All soils contain a mixture of soluble salts, some of which are essential for plant growth. When the total concentration of salts becomes excessive, plant growth is suppressed. The suppression increases

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[†] Deceased.

as the salt concentration increases until the plant dies. Although all plants are subject to stunting, their tolerance threshold and the rate of growth reduction at concentrations above the threshold vary widely among different crop species. Growth suppression seems to be a nonspecific salt effect that is directly related to the total concentration of soluble salts or osmotic potential of the soil water. Within limits, isosmotic concentrations of different combinations of salts cause nearly equal reductions in growth. On the other hand, single salts or extreme ion ratios are likely to cause specific ion effects; namely, ion toxicities or nutritional imbalances. Since saline soils in the field generally consist of a mixture of different salts, specific ion effects are minimal and osmotic effects predominate. Some exceptions to this generalization exist. Woody fruit and nut crops tend to accumulate toxic levels of Cl^- or Na^+ that cause leaf burn, necrosis, and defoliation. Some herbaceous crops, such as soybean, are also susceptible to ion toxicities, but most do not exhibit leaf-injury symptoms even though some accumulate levels of Cl^- or Na^+ that cause injury in woody species.

The relative contribution of osmotic effects and specific ion toxicities on yield are difficult to quantify, however. With most crops, including tree species, yield losses from osmotic stress can be significant before foliar injury is apparent. Reports that citrus yield reductions occur without excessive accumulations of Cl^- or Na^+ and without apparent toxicity symptoms indicate that the dominant effect is osmotic [6–11]. However, salts tend to accumulate in woody tissues over several years before toxic symptoms appear; consequently, the effects of leaf injury and loss can occur dramatically when the salts reach the leaves. When specific ion toxicities occur, the effects on yield are generally additive with the growth-suppressive effects of osmotic stress. Besides causing specific toxic effects, salinity can induce nutritional disorders in plants [12,13]. Some specific nutrient deficiencies or imbalances, which vary among species and even among varieties of a given crop, are described later in this chapter and by Grattan and Grieve [14].

Sodic Soils

Sodic soils, previously called alkali soils, contain excess exchangeable Na^+, with 15% or more of the cation-exchange sites in the soil being occupied by Na^+ [15]. These soils may be either saline or nonsaline depending on the concentration of salts present in the soil solution. In nonsaline-sodic soils, the total salt concentrations are low, and this, coupled with high ratios of exchangeable Na^+ to Ca^{2+} and Mg^{2+}, can lead to Ca^{2+} and/or Mg^{2+} deficiencies. These deficiencies, rather than Na^+ toxicity, are frequently the cause of poor growth among nonwoody species. In contrast, saline-sodic soils contain higher concentrations of Ca^{2+} and Mg^{2+} and may therefore remain nutritionally adequate. With saline-sodic soils, salinity effects predominate and the nutritional effects of sodicity are usually absent.

In addition to the nutritional imbalances encountered in sodic soils, the hydraulic conductivity and permeability of both water and air are significantly affected by the deterioration of the soil physical condition caused by the high exchangeable Na^+ content. To alleviate the poor permeability of these soils, the electrolyte concentration in the soil water must be increased. This is accomplished by the addition of gypsum ($CaSO_4$), sulfuric acid, or acid-forming compounds to the soil or irrigation water [16]. The acid and acid-forming compounds react with the soil lime ($CaCO_3$) to release Ca^{2+} into the soil solution. The use of gypsum and the importance of Ca^{2+} in relation to sodic soils and their reclamation have been extensively reviewed by Oster [17] and Rengasamy [18].

Soil Fertility

Plants grown on infertile soils may appear to be more salt tolerant than those grown with adequate fertility. This is because inadequate nutrition depresses yields more under nonsaline than under saline conditions [19,20]. When fertility is low, proper fertilizer applications increase yields regardless of the soil salinity, but proportionally more if the soil is nonsaline [21]. When both salinity and fertility limit yields, decreasing salinity or increasing fertility is beneficial.

Despite some claims to the contrary, fertilizer applications exceeding those required on nonsaline soils do not increase the salt tolerance of plants. Unless salinity causes certain nutritional deficiencies or imbalances, excess applications of N, P, or K rarely alleviate the inhibition of growth by salinity [14]. In fact, additional fertilizer adds to the salinity already present in the soil profile and may aggravate salt injury.

Irrigation Water Quality and Management

The principal criteria to determine irrigation water quality are salinity, sodicity, and specific ion concentrations. However, the effects on crops of a given water are not determined solely by its solute composition. These water quality factors should be considered in relation to the specific conditions under which the water is to be used [22,23]; that is, soil properties, irrigation methods, cultural practices, climatic conditions, and the crop to be grown.

Salinity control is frequently a major concern of irrigation management even though the primary objective of irrigation is to maintain soil water in a range suitable for optimum crop yield. To avoid plant water stress, saline soils should be irrigated when the soil water content is appreciably above the permanent-wilting percentage of the soil, as determined under nonsaline conditions. Plant water stress is a function of total soil water potential, which includes both matric and osmotic potential components. As the soil dries, the matric potential decreases, and because the salts are concentrated, the osmotic potential also decreases, further decreasing the total soil water potential.

The extent of permissible water depletion for a given crop is determined by the maximum acceptable salt concentration for that crop [24]. When additional water depletion occurs and no irrigation water is applied to recharge the root zone and dilute this concentrated soil water, yield is reduced. Therefore, increased irrigation frequency is generally required under saline conditions [2]. With shorter irrigation intervals, the concentrating effect for evapotranspiration on soil salinity is minimized [25,26].

Evidence indicates that plants respond primarily to the soil salinity in that part of the root zone with the highest total water potential [25,27]. With more frequent irrigations, this zone corresponds primarily to the upper part of the root zone, where soil salinity is influenced primarily by the salinity of the irrigation water. With infrequent irrigations, the zone of maximum water uptake becomes larger as the plant extracts water from increasingly saline solutions at greater depths.

In soils that are not well drained, the frequency and amount of irrigation water must be closely monitored. Application of excess water over that required for the crop and for leaching should be avoided. Not only are valuable nutrients lost with overirrigation, but flooded or poorly drained soils suffer from poor aeration, which may affect the crop's response to salt stress. Studies have shown that low levels of oxygen interact with salinity to affect shoot growth of tomato [28]. If drainage is inadequate, a shallow water table may develop, which can directly affect the crop response. Plants can extract water directly from this source and, depending on the quality of the water, respond much differently than expected from the level of salinity in the soil.

Most irrigation waters contain more salts than are removed by the crop, so that continued irrigation without leaching progressively salinizes the land. Water in excess of consumptive use (evapotranspiration) must therefore be applied to carry the residual salts out of the root zone. In addition, soils must be sufficiently permeable to allow the extra water needed for leaching to infiltrate in a reasonable time. In practice, it is usually necessary to grow crops for which evapotranspiration is sufficiently less than attainable infiltration to achieve the necessary drainage and salinity control.

Previous studies have shown that salt can be stored in the lower portion of the root zone with only moderate yield reduction, provided the upper portion of the root zone is maintained relatively free of salinity [27,29]. With most irrigation waters and crops, regularity of leaching is not critical. Even when salinities in the lower root zone approximate the tolerable limit for a crop, leaching intermittently can be as effective as leaching every irrigation [25].

Sensitive crops require the drainage of larger percentages of applied water from the root zone to maintain soil water concentrations within tolerable limits. Generally stated, the leaching requirement is inversely proportional to the salt tolerance of the crop [24].

The goal of irrigation management should be increased irrigation efficiency to reduce the amount of infiltrated water that is not used by the plant but passes beyond the root zone as deep percolation. The irrigation reuse of this water and the disadvantages of blending this water with low-salinity water for reuse has been thoroughly reviewed by Rhoades and colleagues [30–32].

PLANT RESPONSE TO CULTURAL PRACTICES

Planting Patterns and Population Density

Failure to obtain a satisfactory stand of furrow-irrigated row crops planted on raised beds is a serious problem in many places. The practice of planting a single row in the center of the bed has frequently resulted in poor seed germination even when the soil is only slightly saline at the time of planting. This is because the wetting fronts from both furrows transport salt in the soil to the center of the bed, where it accumulates. Therefore, whether a single row or double row bed is used, the seed row should be planted near the bed shoulder, where the salt accumulation is the lowest. Another method used to minimize salt accumulation when using single-row beds is to irrigate alternate furrows, so the wetting front carries the salt beyond the seed row to the nonirrigated side of the bed.

With either single- or double-row plants, increasing the depth of water in the furrow can also improve germination in salt-affected soils. Salinity can be controlled even better by using sloping beds, with the seed row planted on the slope just above the irrigation water line. Irrigations move the salt past the seed row to the peak of the bed with this method. Planting in furrows is satisfactory from the standpoint of salinity control but may cause emergence problems from soil crusting or poor aeration.

Increasing plant populations in cotton has been shown effectively to lessen the yield reduction associated with salinity [33,34]. Since nearly all crops are stunted to some degree by salinity, a large portion of the field is without canopy cover. When canopy closure is incomplete and solar radiation is lost to the soil, potential yield is lost. Increasing the number of plants per unit area by decreasing row width compensates for the smaller plant size [33,34]. In contrast, reducing intrarow spacing of cotton showed no effect in maintaining yield [34].

Irrigation Methods

The response of crops to soil and water salinity depends on the method of irrigation and the frequency of water application [35–38]. Numerous irrigation systems are used to apply water to crops, but except for minor variations, they all fall within one of the following categories: gravity, sprinkler, or drip. The differences in water distribution by these systems directly affect the distribution of soil salinity in the root zone. In flooded or fully sprinkled soils, water and salt movement is essentially downward, or one dimensional. In furrow-irrigated soils, water flow is two dimensional; that is, both downward and lateral. When water is applied in small flooded basins or by minisprinklers or drip emitters, flow is three dimensional. This method is used primarily with tree or vine crops. Because water and salt move radially away from the source, salts tend to accumulate at the periphery of the wetted zone. This concentration of salts at the outer edges of the root zone can be a problem for plants when winter rains wash the salts back into the root zone.

Crops irrigated with sprinkler irrigation are subject to injury not only from salts in the soil but also from salts absorbed directly through wetted leaf surfaces [39]. In tree crops, the extent that leaves are wetted can be minimized by sprinkling under the canopy. However, even with undercanopy sprinklers, severe damage of the lower leaves can occur [40]. The extent of foliar injury depends on the concentration of salt in the leaves, but weather conditions and water stress can influence the onset of injury. For instance, salt concentrations that cause severe leaf injury and necrosis after a day or two of hot, dry weather may not cause any symptoms while the weather remains cool and humid. Numerous factors affect the amount of salt accumulated by leaves, including the leaf age, shape, angle, and position on the plant, the type and concentration of salt, the ambient temperature

TABLE 1 Relative Susceptibility of Crops to Foliar Injury from Saline Sprinkling Waters: Na or Cl Concentration ($\mathrm{mmol_c\ L^{-1}}$) Causing Foliar Injury[a]

<5	5–10	10–20	>20
Almond	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Corn	Sugar beet
Plum	Tomato	Cucumber	Sunflower
		Safflower	
		Sesame	
		Sorghum	

[a] Susceptibility based on direct accumulation of salts through the leaves. Foliar injury is influenced by cultural and environmental conditions. These data are presented only as general guidelines for daytime sprinkling.

Source: Data compiled from Refs. 38 and 41–44.

and humidity, and the length of time the leaf remains wet. In addition, the leaf surface properties, such as a waxy cuticular layer or pubescence, may restrict ion absorption.

Susceptibility to foliar injury varies considerably among crop species (Table 1). A comparative study by Maas et al. [44] with 11 herbaceous species revealed wide differences in the rates of Na^+ and Cl^- absorption when the plants were sprinkled with saline water. Leaves of deciduous fruit trees (almond, apricot, and plum) appear to absorb Na^+ and Cl^- even more readily than herbaceous crops [41]. Citrus leaves absorbed these ions more slowly but in amounts adequate to cause severe leaf burn [40].

Francois and Clark [42] reported a linear increase in Na^+ and Cl^- concentration in grape leaves when sprinkled with saline water. When Cl^- is readily absorbed directly by the leaves, chloride-resistant grape rootstocks that reduce Cl^- uptake by the roots would be of little benefit with sprinkler irrigation.

If sprinkler irrigation must be used, then good water management is essential. Since foliar injury is related more to frequency of sprinkling then duration [42,43], infrequent, heavy irrigations should be applied rather than frequent, light irrigations. Slowly rotating sprinklers that allow drying between cycles should be avoided, since this increases the wetting-drying frequency. Sprinkling should be done at night or in the early morning when evaporation is less. Hot, dry, windy days should be avoided. In general, poorer quality water can be used for surface-applied irrigation than can be used for sprinkler irrigation.

PLANT RESPONSE TO THE AERIAL ENVIRONMENT

The influence of environmental factors significantly affects the response of plants to salinity. Most crops can tolerate greater salt stress when the weather is cool and humid than when it is hot and dry. Magistad et al. [45], working with identical soil salinities, showed that crops grown in a coastal climate (cool and humid) consistently produced higher yields than those grown in a desert climate (hot and dry). Hoffman and Rawlins [46] reported that the salt tolerance of kidney beans grown with cool temperatures and high relative humidity was more than double that obtained with high-temperature, low-humidity conditions.

These factors also affect the expression of specific salt-injury symptoms. Fruit crops and woody plants, susceptible to leaf injury by excess Cl^- or Na^+ accumulation, often develop leaf necrosis with the onset of hot, dry weather in late spring or early summer [47]. Ehlig [48] reported similar results with grapes, which showed no leaf-injury symptoms during cool, cloudy spring weather even though the leaves contained levels of Cl^- considered toxic.

Although high humidity has been shown consistently to improve growth under salt stress [49], temperature is believed to be the dominant factor in plant response to saline conditions [50]. Other studies have confirmed that temperature influences plant salt tolerance to a greater degree than relative humidity [46,51].

Light intensity has also been implicated in growth reduction caused by salinity. Studies have shown that growth depression from salinity is generally greater under higher than under low-light intensities [52–54]. With citrus, leaf toxicity symptoms are frequently observed on the south side of trees in response to higher light intensities, whereas leaves on the north side may remain symptom free [55].

It is likely that at least part of the reduction in plant growth on saline media is a result of increased transpiration, since high temperature, low relative humidity, and exposure to light are conditions that favor a high rate of transpiration. This may explain why some crops grown outside, where these environmental conditions exist, are more salt sensitive than when the same crop is grown in the greenhouse.

Ozone, a major air pollutant, decreases the yield of some oxidant-sensitive crops more under nonsaline than saline conditions [56–59]. This aberration has the tendency to make many crops grown in air-polluted regions appear to be more salt tolerant than they really are. This salinity-ozone interaction may be agronomically important in air-polluted areas. However, the increased ozone tolerance induced by salinity may be more than offset by the detrimental effects of salinity on the harvestable product [57,58,60].

In contrast to ozone, higher CO_2 concentrations in the atmosphere have been shown to increase the salt tolerance of bean, corn, and tomato [61,62]. This increased tolerance is believed to be the result of an increased rate of photosynthesis [63].

PLANT RESPONSE IN RELATION TO BIOLOGICAL FACTORS

Stage of Growth

Information about the salt tolerance of crops at different stages of growth is extremely limited. Most salt-tolerance data have been obtained from studies in which salinity was relatively constant from seeding to harvest or from the late seedling stage to harvest. These studies provided no information about the salt sensitivity or tolerance at individual stages of growth.

What data are available generally agree that the early seedling stage of growth is the most salt sensitive for most crops [64–68]. It is during this stage of growth with cereal crops that leaf and spikelet primordia are initiated and tiller buds are formed [69]. Consequently, high soil salinity during this stage can severely affect final seed yield.

Although salt stress delays germination and emergence, most crops are capable of germinating at higher salinity levels than they would normally tolerate at the vegetative or reproductive stages of growth [69]. However, this high tolerance is of little benefit when the plants are so much less tolerant during the following seedling stage.

It is generally agreed that after the seedling stage, most plants become increasingly tolerant as growth proceeds through the vegetative, reproductive, and grain-filling stages. Rice may be an exception. Pearson and Bernstein [70] reported that rice yields are significantly reduced if salt stress is imposed at either the seedling stage or during pollination and fertilization. However, a subsequent study by Kaddah [65] did not confirm the salt sensitivity at this latter stage of growth. Increased tolerance with age has also been observed in asparagus, a perennial crop that is much more tolerant after the first year's growth [71].

Influence of Rootstocks

The tolerance of many fruit trees and vine crops can be significantly improved by selecting rootstocks that restrict Cl^- and/or Na^+ accumulation. The Cl^- tolerance levels presented in Table 2 indicate the maximum Cl^- concentrations permissible in soil water that do not cause leaf injury. However, yield of some crops may be decreased without obvious injury symptoms when the osmotic thresholds of the rootstocks are less than these limits.

Although citrus is not considered very salt tolerant, there are differences in salt tolerance among the various rootstocks [55,73,74]. These differences are attributed to salt exclusion, particularly to chloride exclusion [75,76]. Citrus apparently excludes Cl^- from shoots, not by sequestering it in the root but by restricting its entry into and/or movement within the roots. The Cl^- concentration differences found in leaves and to a lesser extent in stems emphasize pronounced rootstock differences in transport of chloride from the root to the shoot [76]. The scion appears to have no major influence on Cl^- transport from the roots to the shoot [77].

Differences among rootstocks is much greater for Cl^- accumulation than for Na^+, and there appears to be no correlation between Cl^- tolerance and Na^+ tolerance [78]. These differences are due to the existence of apparent separate mechanisms that operate to limit or regulate the transport of Na^+ or Cl^- to the leaves [72].

The Cl^- tolerance range for avocado rootstocks is much narrower than for citrus. In addition,

TABLE 2 Chloride Tolerance Limits of Some Fruit Crop Rootstocks

Crop	Rootstock	Maximum permissible Cl^- in soil water without leaf injury[a] (mol m^{-3})
Citrus		
(*Citrus* spp.)	Mandarin (Sunki, Cleopatra), grapefruit, Rangpur lime	50
	Rough lemon,[a] tangelo (Sampson, Minneola), sour orange, Ponkan mandarin	30
	Citrumelo 4475, Calamondin, sweet orange, trifoliate orange, Cuban shaddock, Citrange (Savage, Rusk, Troyer)	20
Grape		
(*Vitis* spp.)	Salt Creek, 1613-3	80
	Dog Ridge	60
	Thompson seedless, Perlette	40
	Cardinal, black rose	20
Stone fruit		
(*Prunus* sp.)	Marianna	50
	Lovell, Shalil	20
	Yunnan	15
Avocado		
(*Persea americana*)	West Indian	15
	Guatemalan	12
	Mexican	10

[a] For some crops, these concentrations may exceed the osmotic threshold and cause some yield reduction. Data from Australia indicate that rough lemon is more sensitive to Cl^- than sweet orange [72].

Source: Adapted from Ref. 21.

because of the wide variation among varieties of the same rootstock, the rootstock tolerances tend to overlap [79]. However, it is generally agreed that the average Cl^- tolerance is West Indian > Guatemalan > Mexican [78–80]. The general pattern for Na^+ accumulation with avocado rootstocks tends to follow that for Cl^- accumulation and, like Cl^-, shows differences among varieties on the same rootstock [80,81].

Cold hardiness has been implicated in the salt tolerance of citrus and avocado rootstocks. Wutscher [82] reported that citrus rootstocks, which have good Cl^--excluding characteristics, tend to be relatively cold hardy. For some citrus species, a short-term, moderate salt stress has been shown to enhance cold hardiness in seedlings by modifying growth, water relations, and mineral nutrition [83].

In contrast to citrus, the more salt tolerant avocado rootstocks, such as West Indian and West Indian–Guatemalan hybrids, are the least cold tolerant. Likewise, the salt-sensitive Mexican rootstock is the most cold-tolerant [84].

Chloride toxicity has been the principal limiting factor for grapevines grown on their own roots. However, a significant reduction in Cl^- accumulation has been shown to occur in Cl^--sensitive scions grown on Dog Ridge or 1613-3 rootstocks [85]. The salt tolerance of these two rootstocks is probably limited by soil osmotic effects long before Cl^- reaches toxic levels.

Differences Among Cultivars

Most commercially grown cultivars are developed under nonsaline conditions and are not bred to endure salt stress. Therefore, their relative tolerances to salinity are often similar and difficult to measure. In addition, many cultivars developed in the past were derived from a narrow genetic base and thus possessed similar traits. Currently developed cultivars are from a much more diverse genetic base and may therefore possess a wider range of salt tolerance.

Among the crop species that already show some diversity in salt tolerance are Bermuda grass, brome grass, creeping bent grass, rice, wheat, barley, soybean, berseem clover, squash, muskmelon, and strawberry. Cotton and sugar cane also show significant cultivar differences, but these differences occur only at high salinity where yields are below commercially acceptable levels [86,87].

Salt Effects on Nitrogen Fixation and Nodulation

Most *Rhizobium* species are relatively unaffected at soil salinity levels that are less than the tolerance threshold values reported for most leguminous crops (Table 3). At soil salinities greater than their threshold, their ability to survive and fix N may be severely reduced [142–144]. This is particularly important, since legumes that are already weakened by salinity stress will be deprived of essential N fertilization as well.

There appears to be a wide range of tolerance to salinity among the various species of rhizobia. Some strains of *R. meliloti* can survive soil water salinities greater than that of seawater (≈ 46 dS m^{-1}), but most strains of *R. japonicum* grow poorly at salinities of 12 dS m^{-1} [145]. Studies comparing various *Rhizobium* species report the salt tolerance of *R. meliloti* > *R. trifolii* > *R. leguminosarum* > *R. japonicum* [145,146].

The salt effect on rhizobia appeared to be ion specific, with Cl^- salts of Na^+, K^+, and Mg^{2+} being more toxic than corresponding SO_4^{2-} salts [147,148]. In addition, Mg^{2+} ions inhibited growth at a much lower concentration than Na^+ or K^+ [149,150].

Since rhizobia can withstand large increases in salinity, they must be able to regulate and adjust their internal solute concentration. Osmoregulation in *Rhizobium* species grown at high external salt concentrations involves the accumulation of organic and/or inorganic solutes. Although some strains respond to salt stress by increasing their intracellular K^+ level [151], others accumulate organic compounds, such as amino acids, betaine, and carbohydrates, in the cytoplasm [152,153].

TABLE 3 Salt Tolerance of Herbaceous Crops[a]

Crop		Tolerance based on	Salt-tolerance parameters		Rating[d]	Reference
Common name	Botanical name[b]		Threshold[c] EC_e (dS m^{-1})	Slope (% per dS m^{-1})		
Fiber, grain, and special crops						
Artichoke, Jerusalem	*Helianthus tuberosus* L.	Tuber yield	0.4	9.6	MS	88
Barley[e]	*Hordeum vulgare* L.	Grain yield	8.0	5.0	T	89
Bean	*Phaseolus vulgaris* L.	Seed or pods	1.0	19	S	89
Canola	*Brassica campestris* L. [syn. *B. rapa* L.]	Seed yield	—	—	T	U[f]
Canola	*B. napus* L.	Seed yield	—	—	T	U
Chickpea	*Cicer arietinum* L.	Seed yield	—	—	MS	90, 91
Corn[g]	*Zea mays* L.	Ear FW	1.7	12	MS	89
Cotton	*Gossypium hirsutum* L.	Seed cotton yield	7.7	5.2	T	89
Flax	*Linum usitatissimum* L.	Seed yield	1.7	12	MS	89
Guar	*Cyamopsis tetragonoloba* (L.) Taub.	Seed yield	8.8	17	T	92
Kenaf	*Hibiscus cannabinus* L.	Stem DW	8.1	11.6	T	93
Millet, channel	*Echinochloa tumerana* (Domin) J. M. Black	Grain yield	—	—	T	94
Oats	*Avena sativa* L.	Grain yield	—	—	T	95, U
Peanut	*Arachis hypogaea* L.	Seed yield	3.2	29	MS	89
Rice, paddy	*Oryza sativa* L.	Grain yield	3.0[h]	12[h]	S	89
Roselle	*Hibiscus sabdariffa* L.	Stem DW	—	—	MT	96
Rye	*Secale cereale* L.	Grain yield	11.4	10.8	T	97
Safflower	*Carthamus tinctorius* L.	Seed yield	—	—	MT	89
Sesame[i]	*Sesamum indicum* L.	Pod DW	—	—	S	98
Sorghum	*Sorghum bicolor* (L.) Moench	Grain yield	6.8	16	MT	99
Soybean	*Glycine max* (L.) Merrill	Seed yield	5.0	20	MT	89
Sugar beet[j]	*Beta vulgaris* L.	Storage root	7.0	5.9	T	89
Sugar cane	*Saccharum officinarum* L.	Shoot DW	1.7	5.9	MS	89
Sunflower	*Helianthus annuus* L.	Seed yield	—	—	MT	100, U
Triticale	× *Triticosecale* Wittmack	Grain yield	6.1	2.5	T	101

Table 3 Continued

Crop		Tolerance based on	Salt-tolerance parameters		Rating[d]	Reference
Common name	Botanical name[b]		Threshold[c] EC_e (dS m^{-1})	Slope (% per dS m^{-1})		
Wheat	*Triticum aestivum* L.	Grain yield	6.0	7.1	MT	89
Wheat (semidwarf)[k]	*T. aestivum* L.	Grain yield	8.6	3.0	T	102
Wheat, durum	*T. turgidum* L. var. *durum* Desf.	Grain yield	5.9	3.8	T	102
Grasses and forage crops						
Alfalfa	*Medicago sativa* L.	Shoot DW	2.0	7.3	MS	89
Alkali grass, Nuttall	*Puccinellia airoides* (Nutt.) Wats. & Coult.	Shoot DW	—	—	T*	15
Alkali sacaton	*Sporobolus airoides* Torr.	Shoot DW	—	—	T*	15
Barley (forage)[e]	*Hordeum vulgare* L.	Shoot DW	6.0	7.1	MT	89
Bent grass, creeping	*Agrostis stolonifera* L.	Shoot DW	—	—	MS	89
Bermuda grass[l]	*Cynodon dactylon* (L.) Pers.	Shoot DW	6.9	6.4	T	89
Bluestem, Angleton	*Dichanthium aristatum* (Poir.) C. E. Hubb. [syn. *Andropogon nodosus* (Willem.) Nash]	Shoot DW	—	—	MS*	103
Broad bean	*Vicia faba* L.	Shoot DW	1.6	9.6	MS	89
Brome grass, mountain	*Bromus marginatus* Nees ex Steud.	Shoot DW	—	—	MT*	15
Brome grass, smooth	*B. inermis* Leyss	Shoot DW	—	—	MT	89
Buffelgrass	*Pennisetum ciliare* (L.) Link. [syn. *Cenchurs ciliaris*]	Shoot DW	—	—	MS*	103
Burnet	*Poterium sanguisorba* L.	Shoot DW	—	—	MS*	15
Canary grass, reed	*Phalaris arundinacea* L.	Shoot DW	—	—	MT	89
Clover, alsike	*Trifolium hybridum* L.	Shoot DW	1.5	12	MS	89
Clover, berseem	*T. alexandrinum* L.	Shoot DW	1.5	5.7	MS	89
Clover, Hubam	*Melilotus alba* Dest. var. *annua* H. S. Coe	Shoot DW	—	—	MT*	15
Clover, ladino	*Trifolium repens* L.	Shoot DW	1.5	12	MS	89
Clover, Persian	*T. resupinatum* L.	Shoot DW	—	—	MS*	104

Clover, red	*T. pratense* L.	Shoot DW	1.5	12	MS	89
Clover, strawberry	*T. fragiferum* L.	Shoot DW	1.5	12	MS	89
Clover, sweet	*Melilotus* sp. Mill.	Shoot DW	—	—	MT*	15
Clover, white Dutch	*Trifolium repens* L.	Shoot DW	—	—	MS*	15
Corn (forage)[g]	*Zea mays* L.	Shoot DW	1.8	7.4	MS	89
Cowpea (forage)	*Vigna unguiculata* (L.) Walp.	Shoot DW	2.5	11	MS	105
Dallis grass	*Paspalum dilatatum* Poir.	Shoot DW	—	—	MS*	106
Dhaincha	*Sesbania bispinosa* (Linn.) W.F. Wight [syn. *Sesbania aculeata* (Willd.) Poir]	Shoot DW	—	—	MT	107, 108
Fescue, meadow	*Festuca pratensis* Huds.	Shoot DW	—	—	MT*	15
Fescue, tall	*Festuca elatior* L.	Shoot DW	3.9	5.3	MT	89
Foxtail, meadow	*Alopecurus pratensis* L.	Shoot DW	1.5	9.6	MS	89
Glycine	*Neonotonia wightii* [formerly *Glycine wightii* or *javanica*]	Shoot DW	—	—	MS	106, 109
Gram; black	*Vigna mungo* (L.) Hepper [syn. *Phaseolus mungo* L.]	Shoot DW	—	—	S	110
Grama, blue	*Bouteloua gracilis* (HBK) Lag. ex Steud.	Shoot DW	—	—	MS*	15
Guinea grass	*Panicum maximum* Jacq.	Shoot DW	—	—	MT	106
Harding grass	*Phalaris tuberosa* L. var. *stenoptera* (Hack) A. S. Hitchc.	Shoot DW	4.6	7.6	MT	89
Kallar grass	*Leptochloa fusca* (L.) Kunth., formerly *Diplachne fusca* Beauv.	Shoot DW	—	—	T	111
Lablab bean	*Lablab purpureus* (L.) Sweet (syn. Dolichos lablab L.)	Shoot DW	—	—	MS	106
Love grass[m]	*Eragrostis* sp. N. M. Wolf	Shoot DW	2.0	8.4	MS	89
Milk vetch, Cicer	*Astragalus cicer* L.	Shoot DW	—	—	MS*	15
Millet, foxtail	*Setaria italica* (L.) Beauvois	Dry matter	—	—	MS	89
Oat grass, tall	*Arrhenatherum elatius* (L.) Beauvois. ex J. Presl & K. Presl	Shoot DW	—	—	MS*	15
Oats (forage)	*Avena sativa* L.	Straw DW	—	—	T	95, U
Orchard grass	*Dactylis glomerata* L.	Shoot DW	1.5	6.2	MS	89

Table 3 Continued

Crop		Tolerance based on	Salt-tolerance parameters			
Common name	Botanical name[b]		Threshold[c] EC_e ($dS\ m^{-1}$)	Slope (% per $dS\ m^{-1}$)	Rating[d]	Reference
Panic grass, blue	*Panicum antidotale* Retz.	Shoot DW	—	—	MS*	103, 112
Pigeon pea	*Cajanus cajan* (L.) Huth [syn. *C. indicus* (K.) Spreng.]	Shoot DW	—	—	S	110, 113
Rape (forage)	*Brassica napus* L.		—	—	MT*	15
Rescue grass	*Bromus unioloides* HBK	Shoot DW	—	—	MT*	15
Rhodes grass	*Chloris gayana* Kunth.	Shoot DW	—	—	MT	103, 112
Rye (forage)	*Secale cereale* L.	Shoot DW	7.6	4.9	T	97
Rye grass, Italian	*Lolium multiflorum* Lam.	Shoot DW	—	—	MT*	114
Rye grass, perennial	*Lolium perenne* L.	Shoot DW	5.6	7.6	MT	89
Rye grass, Wimmera	*L. rigidum* Gaud.		—	—	MT*	115
Salt grass, desert	*Distichlis spicta* L. var. *stricta* (Torr.) Bettle	Shoot DW	—	—	T*	15
Sesbania	*Sesbania exaltata* (Raf.) V. L. Cory	Shoot DW	2.3	7.0	MS	89
Siratro	*Macroptilium atropurpureum* (DC) Urb.	Shoot DW	—	—	MS	106
Sphaerophysa	*Sphaerophysa salsula* (Pall.) DC	Shoot DW	2.2	7.0	MS	116
Sudan grass	*Sorghum sudanense* (Piper) Stapf	Shoot DW	2.8	4.3	MT	89
Timothy	*Phleum pratense* L.	Shoot DW	—	—	MS*	89
Trefoil, big	*Lotus pedunculatus* Cav.	Shoot DW	2.3	19	MS	89
Trefoil, broadleaf birdsfoot	*L. corniculatus* L. var. *arvenis* (Schkuhr) Ser. ex DC	Shoot DW	—	—	MS	117
Trefoil, narrowleaf birdsfoot	*L. corniculatus* var. *tenuifolium* L.	Shoot DW	5.0	10	MT	89
Vetch, common	*Vicia angustifolia* L.	Shoot DW	3.0	11	MS	89
Wheat (forage)[j]	*Triticum aestivum* L.	Shoot DW	4.5	2.6	MT	102
Wheat durum (forage)	*T. turgidum* L. var. *durum* Desf.	Shoot DW	2.1	2.5	MT	102

Wheat grass, fairway crested	*Agropyron cristatum* (L.) Gaertn.	Shoot DW	7.5	6.9	T	89
Wheat grass, intermediate	*A. intermedium* (Host) Beauvois	Shoot DW	—	—	MT*	118
Wheat grass, slender	*A trachycaulum* (Link) Malte	Shoot DW	—	—	MT	89
Wheat grass, standard crested	*A. sibiricum* (Willd.) Beauvois	Shoot DW	3.5	4.0	MT	89
Wheat grass, tall	*A. elongatum* (Hort) Beauvois	Shoot DW	7.5	4.2	T	89
Wheat grass, western	*A. smithii* Rydb.	Shoot DW	—	—	MT*	15
Wild rye, Altai	*Elymus angustus* Trin.	Shoot DW	—	—	T	89
Wild rye, beardless	*E. Triticoides* Buckl.	Shoot DW	2.7	6.0	MT	89
Wild rye, Canadian	*E. canadensis* L.	Shoot DW	—	—	MT*	15
Wild rye, Russian	*E. junceus* Fisch.	Shoot DW	—	—	T	89
Vegetables and fruit crops						
Artichoke	*Cynara scolymus* L.	Head yield	—	—	MT*	104
Asparagus	*Asparagus officinalis* L.	Spear yield	4.1	2.0	T	71
Bean, common	*Phaseolus vulgaris* L.	Seed yield	1.0	19	S	89
Bean, lima	*P. lunatus* L.	Seed yield	—	—	MT*	119
Bean, mung	*Vigna radiata* (L.) R. Wilcz.	Seed yield	1.8	20.7	S	120
Beet, red[i]	*Beta vulgaris* L.	Storage root	4.0	9.0	MT	89
Broccoli	*Brassica oleracea* L. (botrytis group)	Shoot FW	2.8	9.2	MS	89
Brussels sprouts	*B. oleracea* L. (gemmifera group)		—	—	MS*	
Cabbage	*B. oleracea* L. (capitata group)	Head FW	1.8	9.7	MS	89
Carrot	*Daucus carota* L.	Storge root	1.0	14	S	89
Cassava	*Manihot esculenta* Crantz	Tuber yield	—	—	MS	121, 122
Cauliflower	*Brassica oleracea* L. (botrytis group)		—	—	MS*	
Celery	*Apium graveolens* L. var. *dulce* (Mill.) Pers	Petiole FW	1.8	6.2	MS	123
Corn, sweet	*Zea mays* L.	Ear FW	1.7	12	MS	89
Cowpea	*Vigna unguiculata* (L.) Walp.	Seed yield	4.9	12	MT	105
Cucumber	*Cucumis sativus* L.	Fruit yield	2.5	13	MS	89

Table 3 Continued

Crop			Salt-tolerance parameters			
Common name	Botanical name[b]	Tolerance based on	Threshold[c] EC_e (dS m^{-1})	Slope (% per dS m^{-1})	Rating[d]	Reference
Eggplant	*Solanum melongena* L. var. *esculentum* Nees.	Fruit yield	1.1	6.9	MS	124
Garlic	*Allium sativum* L.	Bulb yield	1.7	10	MS	125
Gram, black or urd bean	*Vigna mungo* (L.) Hepper [syn. *Phaseolus mungo* L.]	Shoot DW	—	—	S	110
Kale	*Brassica oleracea* L. (acephala group)		—	—	MS*	115
Kohlrabi	*Brassica oleracea* L. (gongylodes group)		—	—	MS*	
Lettuce	*Lactuca sativa* L.	Top FW	1.3	13	MS	89
Muskmelon	*Cucumis melo* L. (reticulatus group)	Fruit yield	1.0	8.4	MS	126, 127
Okra	*Abelmoschus esculentus* (L.) Moench	Pod yield	—	—	MS	128, 129
Onion (bulb)	*Allium cepa* L.	Bulb yield	1.2	16	S	89
Onion (seed)	*Allium cepa* L.	Seed yield	1.0	8.0	MS	130
Parsnip	*Pastinaca sativa* L.		—	—	S*	115
Pea	*Pisum sativum* L.	Seed FW	3.4	10.6	MS	131
Pepper	*Capsicum annuum* L.	Fruit yield	1.5	14	MS	89
Pigeon Pea	*Cajanus cajan* (L.) Huth [syn. *C. indicus* (K.) Spreng.]	Shoot DW	—	—	S	110, 113
Potato	*Solanum tuberosum* L.	Tuber yield	1.7	12	MS	89
Pumpkin	*Cucurbita pepo* L. var. *Pepo*		—	—	MS*	
Purslane	*Portulaca oleracea* L.	Shoot FW	6.3	9.6	MT	132
Radish	*Raphanus sativus* L.	Storage root	1.2	13	MS	89
Spinach	*Spinacia oleracea* L.	Top FW	2.0	7.6	MS	89
Squash, scallop	*Cucurbita pepo* L. var. *melopepo* (L.) Alef.	Fruit yield	3.2	16	MS	133

Squash, zucchini	*C. pepo* L. var. *melopepo* (L.) Alef.	Fruit yield	4.7	9.4	MT	133
Strawberry	*Fragaria x Ananassa* Duch.	Fruit yield	1.0	33	S	89
Sweet potato	*Ipomoea batatas* (L.) Lam.	Fleshy root	1.5	11	MS	89
Tepary bean	*Phaseolus acutifolius* Gray		—	—	MS*	134–136
Tomato	*Lycopersicon lycopersicum* (L.) Karst. ex Farw.	Fruit yield	2.5	9.9	MS	89
Tomato, cherry	*L. lycopersicum* L. var. *cerasiforme* (Dunal) Alef.	Fruit yield	1.7	9.1	MS	137
Turnip	*Brassica rapa* L. (rapifera group)	Storage root	0.9	9.0	MS	138
Turnip (greens)	*Brassica rapa* L. (rapifera group)	Top FW	3.3	4.3	MT	138
Watermelon	*Citrullus lanatus* (Thunb.) Matsum. & Nalai	Fruit yield	—	—	MS*	104
Winged bean	*Psophocarpus tetragonolobus* L. DC	Shoot DW	—	—	MT	139

EC_e, electrical conductivity of the saturated-soil extract; FW, fresh weight; DW, dry weight; S, sensitive; MS, moderately sensitive; MT, moderately Tolerant; T, tolerant.

[a] These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary depending on climate, soil conditions, and cultural practices.

[b] Botanical and common names follow the convention of *Hortus Third* [140] when possible.

[c] In gypsiferous soils, plants tolerate EC_e about 2 dS m^{-1} higher than indicated.

[d] Ratings are defined by the boundaries in Figure 1. Ratings marked by an asterisk are estimates

[e] Less tolerant during seedling stage, EC_e at this stage should not exceed 4 or 5 dS m^{-1}.

[f] Unpublished U.S. Salinity Laboratory data.

[g] Grain and forage yields of DeKalb XL-75 grown on an organic muck soil decreased about 26% per dS m^{-1} above a threshold of 1.9 dS m^{-1} [141].

[h] 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.

[i] Sesame cultivars Sesaco 7 and 8 may be more tolerant than indicated by the sensitivity rating.

[j] Sensitive during germination and emergence, EC_e should not exceed 3 dS m^{-1}.

[k] Data from one cultivar, Probred.

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

[m] Average for Boer, Wilman, Sand, and Weeping cultivars. Lehmann seems about 50% more tolerant.

SALT–TOLERANCE DATA

Yield-Response Functions

Yield-response curves indicate that most crops tolerate salinity up to a threshold level above which yields decrease approximately linearly as salinity increases. Maas and Hoffman [89] proposed a two-piece linear response model to characterize the curves. The two parameters obtained from this model are the threshold, the maximum allowable salinity without yield reduction, and the slope, the percentage yield decrease per unit increase in salinity beyond the threshold. Table 3 presents these yield-response parameters for many field, forage, vegetable, and fruit crops. The data are presented in terms of the electrical conductivity of the saturated-soil extract, EC_e [15] at 25°C with units of decisiemens per meter ($1\ dS\ m^{-1} = 1\ mmho\ cm^{-1}$). These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending on climate, soil conditions, and cultural practices.

The threshold and slope obtained from the model can be used to calculate relative yield Y_r for any given soil salinity exceeding the threshold by using the equation

$$Y_r = 100 - B(EC_e - A)$$

where A = the salinity threshold expressed in $dS\ m^{-1}$; B = the slope expressed in % per $dS\ m^{-1}$; and EC_e is the mean electrical conductivity of the saturated-soil extract of the root zone [89].

The data in Table 3 apply to soils in which Cl^- is the predominant anion. The EC_e of saturated soil paste from gypsiferous soils (nonsodic, low Mg^{2+}) generally ranges from 1 to 3 $dS\ m^{-1}$ higher than that from nongypsiferous soils with the same conductivity in the soil water at field capacity [154]. The higher salinities are the result of gypsum dissolution during preparation of the soil paste. The extent of this dissolution depends on the exchangeable ion composition, cation-exchange capacity, and solution composition. Therefore, plants grown on gypsiferous soils tolerate salinity levels approximately 2 $dS\ m^{-1}$ higher than those indicated in Table 3.

The salt-tolerance classifications in Figure 1 are presented for quick comparisons among crops. Division boundaries for the classes were chosen to correspond with previously published salt-tolerance terminology ranging from sensitive to tolerant. Generally, the threshold and linear slope for

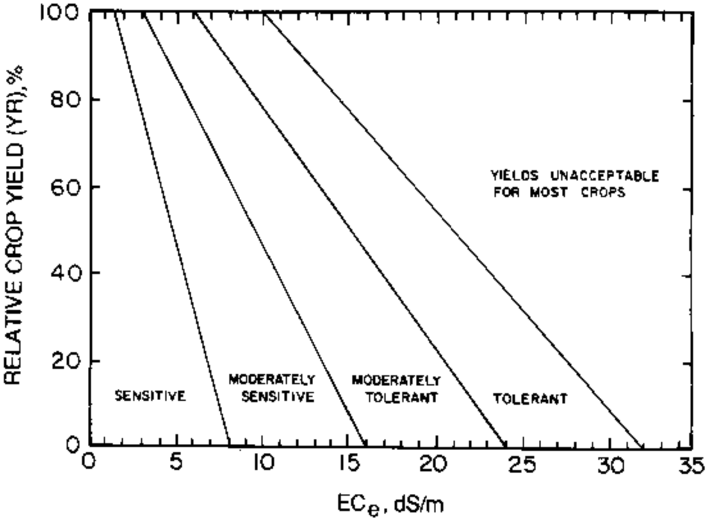

FIGURE 1 Divisions for classifying crop tolerance to salinity.

a crop remain within one class. Where the linear curve for a crop crossed division boundaries, the crop was classified based on the tolerance at lower salinity levels at which yields are commercially acceptable. Classification for some crops in Table 3 are listed with only a qualitative rating, because the data are insufficient to calculate the threshold and slope.

Salt Tolerance of Vegetable Crops

Vegetable crops tend to fall into the more sensitive salt-tolerant categories. The only notable exceptions are asparagus, red beet, and zucchini squash. Since most vegetables are salt sensitive, the choice of land and/or irrigation water where they can be successfully grown is severely restricted. Under marginal conditions of salinity, the growth of many vegetables is stunted without showing other visible injury symptoms [155]. At high salinity levels, some vegetables exhibit pronounced injury symptoms in the later stages of growth. Bean leaves develop a marginal chlorosis-necrosis with an upward cupping of the leaves [156]. Onions have also been shown to develop a leaf necrosis [157]. In addition to growth suppression, some vegetable crops exhibit symptoms of nutritional imbalance or deficiency. Some lettuce cultivars develop calcium-deficiency symptoms when sulfate levels in the soil are too high. Excessive calcium may restrict the uptake of potassium, which may be a factor in reduced yields of bean and carrot [158]. With most vegetable crops, however, the osmotic effect predominates and nutritional effects are either absent or of decidedly secondary importance.

High levels of exchangeable Na^+ frequently restrict vegetative growth because of the unfavorable physical conditions associated with sodic soils. Most vegetable crops appear to be at least moderately tolerant to exchangeable Na^+. Bean plants, however, are sensitive to nutritional factors in sodic soils and may be severely affected even before the physical condition of the soil is impaired.

Most vegetable crops produced on saline soils are not of prime market quality. This is seen in such diverse ways as smaller fruit size of tomatoes and peppers [158], reduced petiole length of celery [123], and misshapen potatoes [159]. It has been generally observed, however, that tomato yields are reduced more by decreases in fruit number than in fruit size or weight [160,161]. Not all salinity effects on quality are detrimental. The flavor of carrots [162] and asparagus [71] is enhanced by a measurable increase in sugar content when grown under saline conditions. Likewise, a number of studies [160,163–165] have shown that total soluble solids in tomatoes is significantly increased as salt stress is increased. Unfortunately, this gain in quality is more than offset by lower yields.

Salt Tolerance of Cereal Crops

Most of the major cereal crops exhibit high tolerance to soil salinity. In this group are sorghum, wheat, triticale, rye, oats, and barley. The only exceptions are corn and rice [21].

Regardless of the overall salt tolerance, all cereals tend to follow the same sensitivity or tolerance pattern in relation to their stage of growth. The seedling or early vegetative stage appears to be the most sensitive, with subsequent stages showing increased tolerance. This phenomenon has been reported for sorghum [67], wheat [66], barley [64], corn [166], and rice [70]. The other cereal crops, although not tested but with similar growth patterns, are also expected to show sensitivity at the early vegetative stage of growth.

Since the life cycle of cereals is an orderly sequence of developmental events, salinity stress can have a significant effect on the developmental process occurring at a particular time. The sequence of events has been separated into three distinct but continuous developmental phases [69]. In the first phase, which encompasses the early vegetative growth stage, leaf and spikelet primordia are initiated, leaf growth occurs, and tiller buds are produced in the axils of the leaves. High soil salinity at this time reduces the number of leaves per culm, the number of spikelets per spike, and the number of tillers per plant [69,167]. Differentiation of the terminal spikelet signals completion of this phase.

During phase II, the tillers grow, mainstem and tiller culms elongate, and the final number of florets is set [168]. Salinity stress during this phase may affect tiller survival and reduce the number of functional florets per spikelet. This phase ends with anthesis. Carpel fertilization and grain filling occur during the final phase [168]. At this time, salinity affects seed number and seed size.

The effect of salinity on spikelet and tiller number established during phase I has a greater influence on final seed yield than the effects exerted on yield components in the latter two phases [66,67,166].

Salt Tolerance of Forage Crops

Forage crops fall into two broad salt-tolerance categories. Most grasses belong to the tolerant group, with the majority of legumes being in the sensitive group. Exceptions to this generalization are meadow foxtail (*Alopecurus pratensis*), love grass (*Eragrostis* spp.), and orchard grass (*Dactylis glomerata*), which are moderately sensitive to salt stress, and birdsfoot trefoil (*Lotus corniculatus* var. *tenuifolium*) and the sweet clovers (*Melilotus* spp.), which are moderately tolerant [89].

Many of the forage grasses possess the same growth habit as the cereal grasses and, like the cereals, are more sensitive to salinity during the early seedling stage of growth [169]. Unlike the cereals, however, many of the grasses are maintained in a perpetual vegetative stage of growth from continued grazing or mowing. Therefore, it appears that these grasses, once they are beyond the early seedling stage and well established, are less sensitive to soil salinity.

Because of their fibrous roots, grasses alone or in combination with forage legumes are frequently used in the reclamation of saline and sodic soils to restore good soil structure [170]. Under nonirrigated conditions, grasses that accumulate significantly high concentrations of Na^+ and Cl^- in the shoots may be used to restore soil structure and also to remove these ions from the soil profile [171]. Grasses used for this purpose may be unfit for animal feed because of the high salt content [170].

Clovers are the predominant legume of pastures and are frequently grown in combination with various grass species. However, salt-sensitive clovers tend to die out on saline soils as the more tolerant grass becomes the predominant vegetation. Loss of the clover from the pasture mixture significantly reduces the nutritional value of the pasture [172].

The salt tolerance of clovers [173] and alfalfa [174] is highly dependent on the stage of growth at which salinity is first imposed. The salt tolerance of alfalfa has been reported to be closely associated with Cl^- accumulation in the leaves [174,175]. Salt-affected plants are characterized initially by a dark green leaf coloration and reduced leaf size [175] followed by a general reduction in plant size [12].

Although the salt tolerance of alfalfa appears to depend on a salt-exclusion mechanism [175], no consistent correlation seems to exist between salt tolerance and salt exclusion for legumes in general [176]. There appears to be sufficient evidence that the genetic variability that exists among the grass and legume species and cultivars offers the possibility of developing strains with higher salt tolerance [169,173,176–178].

Salt Tolerance of Fruit Tree and Vine Crops

With the exception of date palm and a few others believed to be moderately tolerant, most fruit trees are relatively sensitive to salinity (Table 4). Stone fruits, citrus, and avocado have all shown specific sensitivity to foliar accumulations of Cl^- and Na^+. The accumulation of these ions to harmful levels, as well as the general osmotic growth inhibition, contribute to the reduction in tree growth and fruit yield.

Different cultivars and rootstocks absorb Cl^- and Na^+ at different rates, so tolerance can vary

Table 4 Salt Tolerance of Woody Crops[a]

Crop			Salt tolerance parameters			
Common name	Botanical Name[b]	Tolerance based on	Threshold[c] EC_e (dS m^{-1})	Slope (% per dS m^{-1})	Rating[d]	Reference
Almond	*Prunus duclis* (Mill.) D. A. Webb	Shoot growth	1.5	19	S	89
Apple	*Malus sylvestris* Mill.		—	—	S	89
Apricot	*Prunus armeniaca* L.	Shoot growth	1.6	24	S	89
Avocado	*Persea americana* Mill.	Shoot growth	—	—	S	89
Banana	*Musa acuminata* Colla	Fruit yield	—	—	S	179
Blackberry	*Rubus macropetalus* Doug. ex Hook	Fruit yield	1.5	22	S	89
Boysenberry	*Rubus ursinus* Cham. & Schlechtend	Fruit yield	1.5	22	S	89
Castor bean	*Ricinus communis* L.		—	—	MS*	15
Cherimoya	*Annona cherimola* Mill.	Foliar injury	—	—	S	180
Cherry, sand	*Prunus besseyi* L. H. Bailey	Foliar injury, stem growth	—	—	S*	182
Cherry, sweet	*Prunus avium* L.		—	—	S*	181
Coconut	*Cocos nucifera* L.		—	—	MT*	183
Currant	*Ribes* sp. L.	Foliar injury, stem growth	—	—	S*	181,182
Date palm	*Phoenix dactylifera* L.	Fruit yield	4.0	3.6	T	89
Fig	*Ficus carica* L.	Plant DW	—	—	MT*	15,184
Gooseberry	*Ribes* sp. L.		—	—	S*	181
Grape	*Vitis vinifera* L.	Shoot growth	1.5	9.6	MS	89
Grapefruit	*Citrus* × *paradisi* Macfady.	Fruit yield	1.2	13.5	S	7
Guava	*Psidium guajava* L.	Shoot and root growth	4.7	9.8	MT	185

TABLE 4 Continued

Crop			Salt tolerance parameters			
Common name	Botanical Name[b]	Tolerance based on	Threshold[c] EC_e (dS m^{-1})	Slope (% per dS m^{-1})	Rating[d]	Reference
Guayule	*Parthenium argentatum* A. Gray	Shoot DW	8.7	11.6	T	186
Guayule	*Parthenium argentatum* A. Gray	Rubber yield	7.8	10.8	T	186
Jambolan plum	*Syzygium cumini* L.	Shoot growth	—	—	MT	187
Jojoba	*Simmondsia chinensis* (Link) C. K. Schneid	Shoot growth	—	—	T	188,189
Jujube, Indian	*Ziziphus mauritiana* Lam.	Fruit yield	—	—	MT	190
Lemon	*Citrus limon* (L.) Burm. f.	Fruit yield	1.5	12.8	S	9
Lime	*Citrus aurantiifolia* (Christm.) Swingle		—	—	S*	
Loquat	*Eriobotrya japonica* (Thunb.) Lindl.	Foliar injury	—	—	S*	115,191
Macadamia	*Macadamia integrifolia* Maiden & Betche	Seedling growth	—	—	MS*	192
Mandarin orange; tangerine	*Citrus reticulata* Blanco	Shoot growth	—	—	S*	193
Mango	*Mangifera indica* L.	Foliar injury	—	—	S	180
Natal plum	*Carissa grandiflora* (E. H. Mey.) A. DC	Shoot growth	—	—	T	47
Olive	*Olea europaea* L.	Seedling growth, Fruit yield	—	—	MT	89
Orange	*Citrus sinensis* (L.) Osbeck	Fruit yield	1.3	13.1	S	6,8,10,194

Papaya	*Carica papaya* L.	Seedling growth, foliar injury	—	—	MS	195,196
Passion fruit	*Passiflora edulis* Sims.		—	—	S*	115
Peach	*Prunus persica* (L.) Batsch	Shoot growth, Fruit yield	1.7	21	S	89
Pear	*Pyrus communis* L.		—	—	S*	15
Pecan	*Carya illinoinensis* (Wangenh.) C. Koch	Nut yield, trunk growth	—	—	MS	197
Persimmon	*Diospyros virginiana* L.		—	—	S*	115
Pineapple	*Ananas comosus* (L.) Merrill	Shoot DW	—	—	MT	198
Pistachio	*Pistacia vera* L.	Shoot growth	—	—	MS	199,200
Plum, prune	*Prunus domestica* L.	Fruit yield	2.6	31	MS	201
Pomegranate	*Punica granatum* L.	Shoot growth	—	—	MS	202
Popinac, white	*Leucaena leucocephalia* (Lam.) de Wit [syn. *Leucaena glauca* Benth.]	Shoot DW	—	—	MS	203,204
Pummelo	*Citrus maxima* (Burm.)	Foliar injury	—	—	S*	205
Raspberry	*Rubus idaeus* L.	Fruit yield	—	—	S	89
Rose apple	*Syzygium jambos* (L.) Alston	Foliar injury	—	—	S*	206
Sapote, white	*Casimiroa edulis* Llave	Foliar injury	—	—	S*	180
Scarlet wisteria	*Sesbania grandiflora*	Shoot DW	—	—	MT	207
Tamarugo	*Prosopis tamarugo* Phil.	Observation	—	—	T	208
Walnut	*Juglans* spp.		—	—	S*	181

Abbreviations as in Table 3.

[a] These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary depending on climate, soil conditions, and cultural practices. The data are applicable when rootstocks are used that do not accumulate Na^+ or Cl^- rapidly or when these ions do not predominate in the soil.

[b] Botanical and common names follow the convention of *Hortus Third* [140] when possible.

[c] In gypsiferous soils, plants tolerate EC_e about 2 dS m^{-1} higher than indicated.

[d] Ratings are defined by the boundaries in Figure 1. Ratings marked by an asterisk are estimates.

considerably within a species. In the absence of specific ion effects, however, the tolerance of these crops can be expressed as a function of the concentration of total soluble salts or the osmotic potential of the soil solution.

Some of the more sensitive fruit crops may accumulate toxic levels of Na^+ and/or Cl^- over a period of years from soils that would be classified as nonsaline and nonsodic [209,210]. Chloride toxicity in woody species is generally more severe and is observed on a wider range of species than Na^+ toxicity. The differences among species, cultivars, or rootstocks in susceptibility to Cl^- usually reflect the capability of the plant to prevent or retard Cl^- accumulation in the plant tops.

The initial symptoms of excess Cl^- accumulation in fruit crops is leaf tip necrosis developing into marginal necrosis. With citrus, a chlorosis and bronzing of the leaves occur without a well-defined necrosis. As Cl^- continues to accumulate, the effects become more severe with premature leaf drop, complete defoliation, twig dieback, and in extreme cases death of the tree or vine [210,211].

Injury by Na^+ can occur at concentrations as low as 5 mol m^{-3} in the soil solution [21]. However, injury symptoms, which are characterized as tip, marginal, and/or interveinal necrosis, may not appear for a considerable time after exposure to salinity. Initially, the Na^+ is thought to be retained in the sapwood of the tree. With the conversion of sapwood to heartwood, the Na^+ is released and then translocated to the leaves, causing leaf burn [212]. This may partly explain why stone fruits and grapes appear to be more sensitive to salinity as the plants grow older. With succeeding years, the Cl^- and Na^+ accumulate more rapidly in the leaves, causing leaf burn to develop earlier and with increasing severity [201].

Recent studies have shown that Na^+ accumulation in plum leaves did not significantly increase until the leaves were already severely damaged by Cl^- accumulation [201].

These studies indicate that when Cl^- and Na^+ are present in the soil solution, Cl^- is the primary damaging ion on stone fruits. Sodium accumulation only occurs after the leaf membranes have already been damaged.

Growth and yield reduction may occur with woody fruit species in the absence of specific ion toxicity. Francois and Clark [213], working with Valencia orange, reported a 50% reduction in fruit yield from salinity with no visible leaf-injury symptoms. Once salts have accumulated to toxic levels, however, growth and yield are suppressed by the additive effects of osmotic stress and specific ion toxicities [210].

Salt Tolerance of Ornamentals, Trees, and Flowers

In contrast to crop species that produce a marketable product, the salt tolerance of ornamental shrubs, trees, and flowers is determined by the esthetic value of the plant species. Injury or loss of leaves or flowers caused by salt stress is unacceptable even though growth may be unaffected. A significant growth reduction might be acceptable and possibly desirable for some species, as long as they appear to be healthy and attractive. The salt tolerance limits presented in Table 5 for some ornamental shrubs, trees, and ground covers indicate the maximum permissible EC_e for an acceptable appearance.

The type of injury seen on woody ornamentals and trees is similar to damage recorded for fruit trees and vines. A number of reports have shown that although some species accumulate Na^+, salt tolerance is closely associated with their ability to limit Cl^- uptake and accumulation [214,216,217].

In northern climates, where NaCl and/or $CaCl_2$ are used as deicing salts, typical salt-injury symptoms occur on roadside trees. These trees are subjected to both soil salinity from runoff and saline spray from passing automobiles. Although salt spray is thought to be the more detrimental of the two modes of deposition [218,219], soil-salinity effects may be accumulative and over a period of years may result in a slow but progressive decline of the trees.

A limited number of floricultural plants have been tested for salt tolerance. Chrysanthemum, carnation, and stock are considered moderately tolerant to salt stress; aster, poinsettia, gladiolus,

Table 5 Salt Tolerance of Ornamental Shrubs, Trees, and Ground Cover[a]

Common name	Botanical name	Maximum permissible soil salinity[b] EC_e (dS m^{-1})
Very sensitive		
Star jasmine	*Trachelospermum jasminoides* (Lindl.) Lem.	1–2
Pyrenees cotoneaster	*Cotoneaster congestus* Bak.	1–2
Oregon grape	*Mahonia aquifolium* (Pursh) Nutt.	1–2
Photinia	*Photinia* × *Fraseri* Dress.	1–2
Sensitive		
Pineapple guava	*Feijoa sellowiana* O. Berg	2–3
Chinese holly, cv. Burford	*Ilex cornuta* Lindl & Paxt.	2–3
Rose, cv. Grenoble	*Rosa* sp. L.	2–3
Glossy abelia	*Abelia* × *grandiflora* (Andre) Rehd.	2–3
Southern yew	*Podocarpus macrophyllus* (Thunb.) D. Don	2–3
Tulip tree	*Liriodendron tulipifera* L.	2–3
Algerian ivy	*Hedera canariensis* Willd.	3–4
Japanese pittosporum	*Pittosporum tobira* (Thunb.) Ait.	3–4
Heavenly bamboo	*Nandina domestica* Thunb.	3–4
Chinese hibiscus	*Hibiscus rosa-sinensis* L.	3–4
Laurustinus, cv. Robustum	*Viburnum tinus* L.	3–4
Strawberry tree, cv. Compact	*Arbutus unedo* L.	3–4
Crape myrtle	*Lagerstroemia indica* L.	3–4
Moderately sensitive		
Glossy privet	*Ligustrum lucidum* Ait.	4–6
Yellow sage	*Lantana camara* L.	4–6
Orchid tree	*Bauhinia purpurea* L.	4–6
Southern magnolia	*Magnolia grandiflora* L.	4–6
Japanese boxwood	*Buxus microphylla* Siebold & Zucc. var. *japonica* (Mull. Arg) Rehd. & E. H. Wils.	4–6
Xylosma	*Xylosma congestum* (Lour.) Merrill	4–6
Japanese black pine	*Pinus thunbergiana* Franco	4–6
Indian hawthorn	*Raphiolepis indica* (L.) Lindl.	4–6
Dodonaea, cv. atropurpurea	*Dodonaea viscosa* (L.) Jacq.	4–6
Oriental arborvitae	*Platycladus orientalis* (L.) Franco	4–6
Thorny elaeagnus	*Elaeagnus pungens* Thunb.	4–6
Spreading juniper	*Juniperus chinensis* L.	4–6
Pyracantha, cv. Graberi	*Pyracantha fortuneana* (Maxim.) H. L. Li.	4–6
Cherry plum	*Prunus cerasifera* J. F. Ehrh.	4–6
Moderately tolerant		
Weeping bottlebrush	*Callistemon viminalis* (Soland. ex Gaertn.) Cheel.	6–8
Oleander	*Nerium oleander* L.	6–8
European fan palm	*Chamaerops humilis* L.	6–8
Blue dracaena	*Cordyline indivisa* (G. Forst.) Steud	6–8

Table 5 Continued

Common name	Botanical name	Maximum permissible soil salinity[b] EC_e (dS m^{-1})
Spindle tree, cv. Grandiflora	*Euonymus japonica* Thunb.	6–8
Rosemary	*Rosmarinus officinalis* L.	6–8
Aleppo pine	*Pinus halepensis* Mill.	6–8
Sweet gum	*Liquidambar styraciflua* L.	6–8
Tolerant		
Brush cherry	*Syzygium paniculatum* Gaertn.	>8[c]
Ceniza	*Leucophyllum frutescens* (Berland.) I. M. Johnst.	>8[c]
Natal plum	*Carissa grandiflora* (E. H. Mey.) A. DC.	>8[c]
Evergreen pear	*Pyrus kawakamii* Hayata	>8[c]
Bougainvillea	*Bougainvillea spectabilis* Willd.	>8[c]
Italian stone pine	*Pinus pinea* L.	>8[c]
Very tolerant		
White iceplant	*Delosperma alba* N. E. Br.	>10[c]
Rosea iceplant	*Drosanthemum hispidum* (L.) Schwant	>10[c]
Purple iceplant	*Lampranthus productus* N. E. Br.	>10[c]
Croceum iceplant	*Mesembryanthemum croceus* Jacq.	>10[c]

EC_e, electrical conductivity of the saturated-soil extract.

[a] Species are listed in order of increasing tolerance based on appearance as well as growth reduction.

[b] Salinities exceeding the maximum permissible EC_e may cause leaf burn, loss of leaves, and/or excessive stunting.

[c] Maximum permissible EC_e is unknown. No injury symptoms or growth reduction was apparent at 7 dS m^{-1}. The growth of all iceplant species was increased by soil salinity of 7 dS m^{-1}.

Source: Data compiled from Refs. 47, 214, and 215.

azalea, gardenia, gerbera, amaryllis, and African violet are considered somewhat sensitive [220,221]. Like other ornamental species, the esthetic value of floral plants is the determining factor for salt tolerance.

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