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Chapter 17

Soil and Water Salinity

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Definitions and forms of salinity

All natural waters contain soluble salts. The concentration of the salts determines whether the water is of high quality (drinkable or usable for irrigation without need for special precautions) or of low quality (brackish or saline). Water in the soil also contains soluble salts (sometimes called free or nonattached salts). The amount of salts in the root zone (or the salt concentration in the soil solution) determines whether the soil is "normal" or "salt-affected" (saline, sodic, or saline-sodic).

Salinity becomes a concern when an "excessive" amount or concentration of soluble salts occurs in the soil, either naturally or as a result of mismanaged irrigation water. Worldwide, salt-affected soils are most abundant in arid regions, and in irrigated lands the formation of salt-affected soils is the most important process of chemical soil degradation. In Hawaii, salinity is more of a concern in irrigated shoreline areas where groundwater supplies are influenced by intrusion of sea water. Sediments dredged from salt-laden deposits are also chronic problems, particularly when used as fill on which vegetation is attempted. In Hawaii, salinity is generally a cyclical problem related to water availability from rainfall; it is aggravated in dry years and relieved in wet years. Fortunately, most of Hawaii's soils have physical and structural qualities that impart behavioral resilience and prevent salts from imposing irreversible soil degradation.

The most common salts in water and soil solutions are composed of the cations sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) and the anions chloride (Cl^-), sulfate (SO_4^{2-}), and carbonate in the form of bicarbonate (HCO_3^-). Boron, as non-dissociated boric acid, can also be present in significant quantities in certain situations. Data on the total concentration of these constituents, their relative abundance (particularly that of Na^+), and their effect on soil pH are used to categorize the quality of water for irrigation, determine the suitability of soil for cultivation, select crops that are most adaptable for use, and assess the need for soil reclamation.

Sources of salinity

Salts in soil and irrigation water may be either

- naturally present as products of geo-chemical weathering of rocks and parent materials
- derived directly from sea water by flooding, spray, or intrusion into groundwater resources
- caused by irrigation mismanagement, particularly when internal soil drainage is impeded.

The hazard of excessive salt accumulation in irrigated soils increases when leaching of salts from the root zone is not adequately provided for. In this respect, soil salinity avoidance may run counter to the concept of "water use efficiency" if water management is not wisely practiced. In such situations, excess irrigation is not "wasteful." It is a necessity, because irrigation must be applied above and beyond the growing crop's consumptive use in order to meet leaching requirements. As expected, the higher the salinity level, the more leaching is required. Preventing salinization is more feasible, logistically and economically, than reclaiming salt-damaged soils.

Inorganic fertilizers are also salts, but they are seldom considered a salinity hazard because salt build-up in the field must exceed certain levels before plants are adversely affected. However, situations may arise wherein growers of high-value horticultural crops in controlled cultures, pots, or greenhouses may attempt to “maximize” production through excessive fertilization. Also, a significant water quality hazard may arise when the use-efficiency of applied fertilizers is low and excess nonutilized nutrients, notably nitrates and phosphates, can be leached or otherwise transported into water resources.

Measuring and expressing salinity

The concentration of *total dissolved salts* (TDS) may be determined in many ways (Table 17-1), but it is commonly done either by separating and weighing the salts or measuring the electrical conductivity of the soil solution.

1. Direct gravimetric method. A specified volume of an aqueous solution is dried, and the salts contained in it are weighed and expressed as milligrams per liter (mg/L, equivalent to parts per million, ppm) or as grains per gallon (gpg; 1 gpg = 17.1 ppm).

2. Electrical conductivity. Inorganic salts are electrolytes that, in aqueous solutions, are capable of conducting an electric current. The higher the salt concentration, the higher the electrical conductivity (EC). Measured EC values for irrigation water are identified as EC_w). Such measurements are made by specially designed conductivity meters and sensors, and they can be taken either in water or directly in the soil (in situ). The standard unit for EC in the older literature was millimohs per centimeter (mmho/cm); this is equivalent to decisiemens per meter (dS/m) in the SI unit system used in current literature. Because electrical conductance varies with temperature, measurements must be corrected for the prevailing temperature and reported at the standard “room” temperature of 25°C.

Determinations of EC_w and pH for irrigation water are made on freshly collected, representative samples following filtration. Sample storage time should be minimized to avoid changes in water composition. For soils, samples must be carefully collected to be truly representative, because salt distribution in field soils usually varies considerably over both space and time.

Salinity measurements are made on soil-water extracts, the most commonly used being the *saturated soil extract* (or *saturation extract*) obtained from a *saturated soil paste*. After the prepared paste is allowed to stand overnight, its pH is measured, and the extract is then obtained by filtration over a vacuum. The electrical conductivity of this saturation extract (EC_e, expressed as mmho/cm or dS/m at 25°C) is the standard means of quantifying soil salinity. Other water extracts (e.g., from 1:1 or 1:5 soil:water mixtures) can be used, but these do not lend themselves as well to comparisons with other data reported in the soil science literature, to standard interpretation in relation to actual field salinity, or to making direct use of available crop response and tolerance data.

Soil parameters related to salinity

In addition to total salt concentration, the ionic composition of various constituents and the pH are also determined by conventional laboratory procedures. Major cations which occupy the soil’s *exchange complex* (exchangeable Na^+, K^+, Ca^{2+}, and Mg^{2+}) are determined after extraction in ammonium acetate or other appropriate extracts. Other soluble ionic species suspected of contributing to specific crop stress or toxicity problems are similarly determined. Both the concentrations of individual ions and their relative proportions to one another are calculated to allow systematic data interpretation and evaluation of management options. The most important parameter is the *sodium adsorption ratio* (SAR) for water solutions and *exchangeable sodium percentage* (ESP) for soils. SAR = $Na^+ \div [(Ca^{2+} + Mg^{2+}) \div 2]^{1/2}$, where all ionic concentrations

Table 17-1.
Conversions among various units expressing salinity.

Electrical conductivity of water		
1 mho/cm	=	1000 mmhos/cm (millimohs per cm)
1 mmho/cm	=	1000 µmhos/cm (micromohs per cm)
1 dS/m	=	1 mmho/cm
Total salt concentration in water		
1 g/L	=	1 ppt (part per thousand)
1 ppt	=	1000 ppm (parts per million)
17.1 ppm	=	1 gpg (grain per gallon)
1 mmho/cm	=	640 ppm (approximately)
1 mmho/cm	=	10 meq/l (milliequivalents per liter)
1 ppm	=	0.00136 tons/acre-ft

are in milliequivalents per liter. ESP = (exchangeable Na^+ ÷ CEC) x 100, where both values are in milliequivalents. High sodium concentrations (such as in sodic soils) can be toxic to plants, may be destructive to soil structure, and may lead to high pH levels (>8.5) and, ultimately, the development of alkaline conditions.

Interpreting salinity measurements

Data on total salinity and ionic composition should be interpreted in view of

- existing or intended agricultural use
- the characteristics of the soil in question
- the availability and quality of water supplies
- irrigation management plans
- prevailing climatic conditions

The basic evaluation criteria are electrical conductivity and sodium abundance in waters and soils. The standards given in Table 17-2 are suggested for Hawaii.

Table 17-2.
Salinity standards for agricultural situations in Hawaii.

Measurement	Interpretation
Irrigation water	
EC_w value (dS/m at 25°C)	
< 0.75	Little or no hazard to crops (acceptable)
0.75 – 3.0	Increasing hazard (intermediate)
> 3.0	Severe hazard (excessive)
SAR value	
< 10	Acceptable,
10 – 25	Intermediate
> 25	Excessive
Soil	
EC_e value (dS/m at 25°C)	
< 2	Little no effect on the growth and yield of plants,
2 – 4	Affects only very sensitive plants
4 – 8	Affects many plants
8 – 16	Affects tolerant plants
> 16	Affects even very tolerant plants
ESP value	
< 10	Acceptable
10 – 35	Intermediate
> 35	Excessive

Saline soils have been conventionally defined as those with EC_e values of 4 dS/m or higher; *saline sodic soils* are saline soils that also have high percentages of exchangeable sodium. The interpretation of values in the table is particularly suited for Hawaii and is somewhat more liberal than for temperate areas, whose soils are less resistant to the effects of salt and sodium than are Hawaii's well weathered and well structured soils. Saline soils can be reclaimed merely by leaching excess salts. Sodic soils, however, must also be amended with a calcium source to displace excess sodium and allow the recovery of favorable soil structure.

It is important to note that the permissible levels of salinity and ionic constituents are lower for irrigation water than for soils because, following irrigation, salts concentrate in the crop root zone as a result of water loss by evaporation and evapotranspiration. A crude rule of thumb is that such concentration is in the order of 2–4 times.

Certain "minor" chemical constituents of irrigation water or soil solution can also impose severe restrictions on plant growth when present in excessive amounts; these are called toxic or specific-ion effects (see Tables 17-3 to 17-6). Table 17-4 shows similar information for a number of "trace" elements. Boron is the minor constituent of most concern for toxicity in salt-affected soils (Table 17-6).

Plant tolerances of and responses to salinity

High concentrations of soluble salts in the root zone impose physiologic stresses on growing plants. These stresses may be caused by a salt present in soluble (or free) form (osmotic stress). They may also be due to toxic or specific-ion effects, or to nutritional imbalances. Most such stresses can be specified quantitatively. Quantifying a crop's sensitivity to salt requires that we define

- the threshold salinity level below which the crop's performance is unaffected by salinity
- the incremental decline in yield per unit increase in salinity above the threshold level
- the salinity level at which the crop ceases to grow.

Such data are obtained experimentally and are used to plot crop tolerance diagrams that relate relative crop yield to the electrical conductivity of the soil's saturation extract (EC_e). In the appendix to this chapter, the schematic lines in the key show how such data are dis-

Table 17-3. Relative tolerance of exchangeable sodium by some crops and grasses.

Tolerant[y]	Semitolerant	Sensitive
	ESP level for 50% reduction in yield:	
>35	15 – 25	≤15
Karnal grass *(Diplachna fusca)*	Wheat *(Triticum vulgare)*	Cowpeas *(Vigna sinensis)*
Rhodes grass *(Chloris gayana)*	Barley *(Hordium vulgare)*	Gram *(Cicer arietinum)*
Para grass *(Brachiaria mutica)*	Oats *(Avena sativa)* (20 – 40)[z]	Groundnut *(Arachis hypogaea)*
Bermuda grass *(Cynodon dactylon)*	Raya *(Brassica juncea)*	Lentil *(Lens esculenta)*
Rice (*Oryza sativa*) (20 – 40)[z]	Senji *(Melilotus parviflora)*	Mash *(Phaseolus mungo)*
Sugarbeet *(Beta vulgaris)*	Barseem *(Trifolium alexandrinum)*	Mung *(Phaseolus aurus)*
Alfalfa (40 – 60)[z]	Sugarcane *(Saccharum officinarum)*	Peas *(Pisum sativum)*
Barley (40 – 60)[z]	Bajra *(Pennesetum typhoides)*	Maize *(Zea mays)*
Beets (40 – 60)[z]	Cotton *(Gossypium hirsutum)*	Cotton, at germination *(Gossypium hirsutum)*
Carrots	Dwarf red kidney bean	Avocado (2–10)[z]
Onion	Red clover	Green beans (10–15)[z]
Tomatoes (40 – 60)[z]	Lemon	Corn
Wheat (40 – 60)[z]	Lettuce	Tall fescue
	Radish	Peach
	Strawberry	

[y] Crop yields are affected seriously if the ESP is more than about 55, 35, and 10 for tolerant, semitolerant, and sensitive crops, respectively. Tolerance in each column decreases from top to bottom. The grasses listed are highly tolerant and some, like Karnal grass, will grow even in soils of ESP 80 – 90.

[z] Figures for tolerance limits under nonsaline conditions.

played and define, quantitatively, various categories of crop tolerance. These categories also appear on the specific tolerance curves for various crop groups shown. For crops not included in these figures, additional literature search or new research will be needed to retrieve available information.

Additional information

The points in the following paragraphs relate to cropping and managing salt-affected soils.

Crop species as well as cultivars differ in their response to salinity.

Crop growth stages, beginning with germination, can display different sensitivities to salt stress. Generally (but not always), younger stages are more sensitive.

Different salts, cations, and anions vary in their effects on plants and soils, so that waters or soil solutions with similar EC values may not have similar effects if their ionic compositions are different. Specific ion toxicity occurs most commonly due to excessive boron, Cl^-, HCO_3^-, Na^+, and other ions (Tables 17-3–6).

Soil structure and other physical properties may also be sensitive to certain ionic constituents. If structural breakdown occurs, it can exacerbate salt effects on crops through increased surface crusting, germination inhibition, and reduced permeability, porosity, and aeration.

Salinity in the root zone is represented analytically as a single value for the site in question, but it actually fluctuates greatly in time and space. Continuous monitoring of representative locations in affected irrigated fields is more informative than a “snapshot” measurement. Technology now exists that allows continuous monitoring of salinity directly in the field.

Multiple stresses on growing plants are not uncommon in salt-affected soils. Most important are the additive effects of salt and water stress (drought).

Water management is the most readily available modifier of salt stress in the root zone. The amount, frequency, and method of irrigation collectively determine the quantity, status, and distribution of salts in soil. In the absence of sufficient leaching, salts move upward by capillarity in response to evaporation gradients, and they accumulate in different locations on the soil surface. Therefore, seedbed design and seed placement can be done to minimize exposure of seeds and roots to salt, particularly in the early, sensitive stages of growth (see Figure 17-1). Applying irriga-

Table 17-4. Trace element tolerances (mg/liter) for irrigation waters.

Element	Continuous use, all soils	Short-term use, fine-textured soils
Aluminum	1.0	20.0
Arsenic	1.0	10.0
Beryllium	.5	1.0
Boron	0.75	2.0
Cadmium	0.005	0.05
Chromium	5.0	20.0
Cobalt	0.2	10.0
Copper	0.2	5.0
Lead	5.0	20.0
Lithium	5.0	5.0
Manganese	2.0	20.0
Molybdenum	0.005	0.05
Nickel	0.5	2.0
Selenium	0.05	0.05
Vanadium	10.0	10.0
Zinc	5.0	10.0

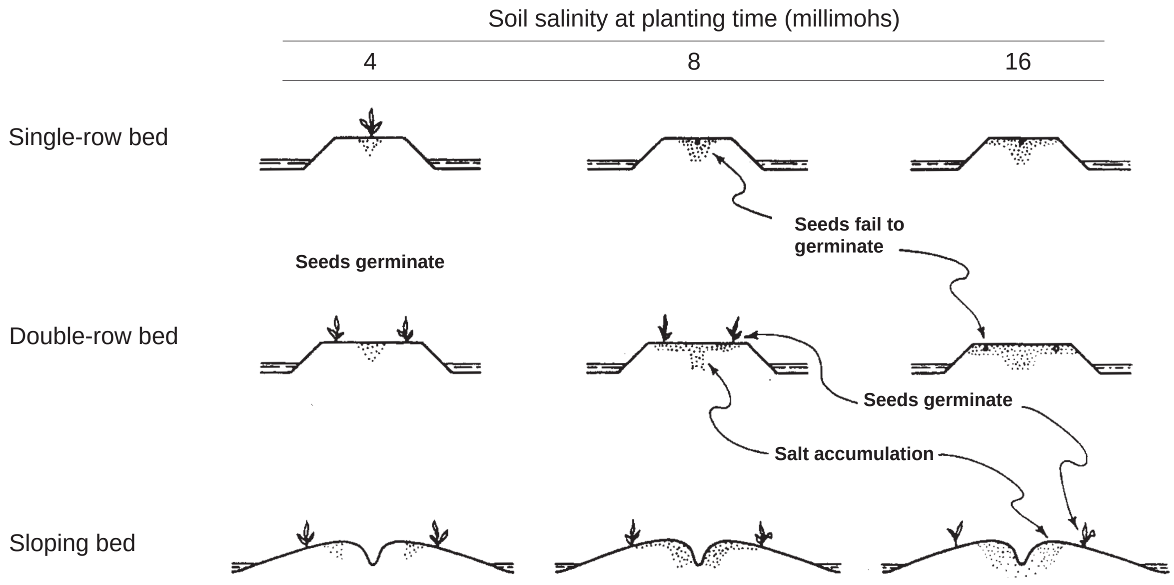
Table 17-5. Crop sensitivity to chloride in soil solution.[z]

Tolerance					
Low		Medium		High	
20% yield reduction at (mg/liter)					
< 19		20 – 24		> 24	
Avocado	(14)	Strawberry	(20)	Gardenia	
Lemon	(15)	Rice	(23)	Wheat, young	(25)
Navy bean	(18)	Alfalfa	(23)	Tomato	(39)
Dallis grass	(19)	Sorghum	(23)	Cotton	(50)
		Kidney beans	(24)	Flax	(50)
				Corn, young	(70)
				Barley	(50)

[z] In irrigation water, problem thresholds for chloride-sensitive crops are (in me/liter chloride content): no problems, <3; moderate problems, 3–9; and severe problems, >9. Source: Doneen 1958.

Figure 17-1. Bed shapes and salinity effects at different levels of soil salinity at planting time.

The pattern of salt build-up depends on bed shape and irrigation method. Seeds sprout only when they are placed so as to avoid excessive salt build-up around them.



(Source: Bernstein et al. 1955.)

tion water in excess of the crop's consumptive use forces the salt to move downward and eventually out of the root zone. Installation of subsurface drainage provisions may be necessary to dispose of such excess water and leached salts.

Sprinkler irrigation with marginal water may be more harmful than other irrigation methods, because many crops are sensitive to salts that directly contact their leaves. Sea spray in shoreline areas may damage certain vegetation.

Table 17-6. Sensitivity to boron in irrigation water.[z]

Sensitive (1 ppm)	Semitolerant (2 ppm)	Tolerant (4 ppm)
Navy bean	Sunflower	Asparagus
Pear	Potato	Date Palm
Apple	Cotton	Sugarbeet
Grape	Tomato	Alfalfa
Persimmon	Sweet pea	Broad bean
Orange	Radish	Onion
Avocado	Field pea	Turnip
Grapefruit	Barley	Cabbage
Lemon	Wheat	Lettuce
	Corn	Carrot
	Milo sorghum	
	Bell pepper	
	Sweet potato	
	Lima bean	

[z]Sensitivity based on symptom appearances and not necessarily yield data.
Source: USSL 1954.

Interpreting salinity data

Examples of analytical data and its interpretation are shown in Tables 17-7 and 17-8.

According to the information on irrigation water in Table 17-7, the Koolau well water, with a very low EC_w and an SAR value of less than 2, is unconditionally suitable for use in irrigating any crop suitable for growing in the area, using any method of irrigation. Indeed, this water—from the chemical perspective—is considered excellent for human consumption as well. On the other hand, the basaltic aquifer sample is of "moderate" quality based on the EC_w value and the SAR

Table 17-7. Examples of analytical data for irrigation water in Hawaii.

		Cations (ppm), [meq/liter]				Anions (ppm), [meq/liter]			
Sample source	EC_w (dS/m)	Na	Ca	Mg	K	Cl	SO_4	HCO_3	SiO_2
Basal Koolau well	0.205	20 [0.88]	8.0 [0.44]	6.0 [0.5]	2.0 [0.05]	22 [0.61]	5.5 [0.12]	65 [1.1]	36 N.A.
Basaltic aquifer, sea-water intruded	2.42	432 [18.8]	31 [1.55]	52 [4.33]	19 [0.49]	767 [21.3]	112 [23.3]	76 [1.25]	79 N.A.

Table 17-8. Examples of analytical data for soils (plow-layer depth) in Hawaii.

				Exchangeable cations (meq/100g)			
Sample source	EC_e (dS/m)	CEC[z] (meq/100 g)	pH in saturated paste	Na	Ca	Mg	K
Irrigated Molokai series, Kunia, Oahu	1.17	11.3	6.8	0.46	5.1	0.33	1.32
Irrigated Molokai (?) series, Lahaina, Maui	6.80	21.7	7.0	6.1	0.7	5.5	0.4

[z]Cation exchange capacity as measured by extraction with pH 7 AmOAc.

of about 7, but is "hazardous" based on the Cl^- concentration exceeding 9 meq/liter. If this water is to be used for irrigation, a predetermined leaching requirement (LR) will be needed to avoid accumulating excessive amounts of salt in the root-zone. Quantitative formulas, which allow computing LR values, combine information on the water's quality and crop tolerance to salinity and show that sensitive crops will require higher leaching requirements than tolerant crops.

Considering the soil data in Table 17-8, the composition of the Kunia sample reflects the long history of irrigation with the very high quality "ditch water" commonly used by plantations in the Pearl Harbor basin. The EC_e and pH values are not limiting to crop growth, and the ESP value of less than 5% is well within the acceptable range for both crops and soils. The Lahaina sample, on the other hand, has a "moderately high" EC_e value, which is expected to bring about salt stress to most crops. The ESP value of about 28% is close to the upper limit of the intermediate quality range. Unless the crop of interest is tolerant of both these excesses, it is necessary to have a management strategy that maximizes salt leaching and displacement of exchangeable sodium by calcium. The most common amendment for the latter purpose is agricultural gypsum ($CaSO_4 \cdot 2H_2O$). The required application can be determined after deciding the value by which ESP exceeds the desired level at the soil depth to be treated (in this case, 28 – 5 = 23). The gypsum amount that is chemically equivalent to this excess sodium can then be calculated (a detailed example is provided in El-Swaify et al. 1983). Most of Hawaii's soils are structurally tolerant to exchangeable sodium, so that soil permeability will generally remain favorable during the reclamation process.

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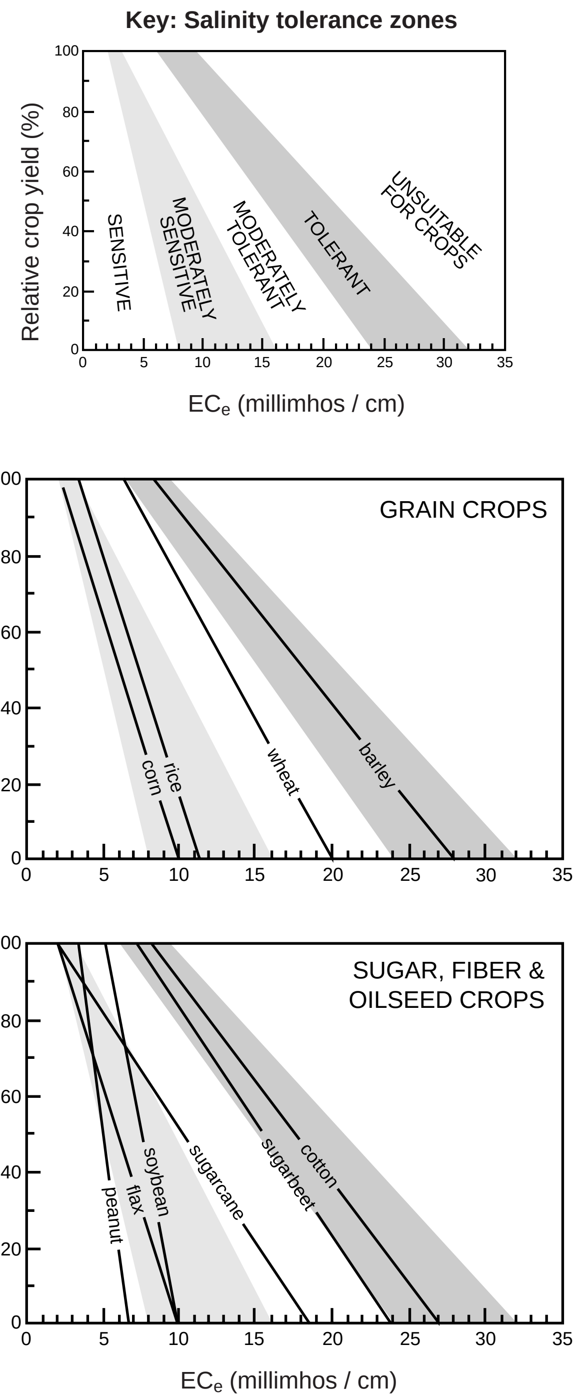
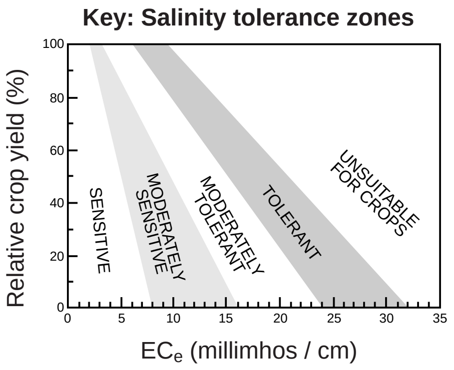
Maas, E.V., and G.J. Hoffman. 1977. Crop salt tolerance: evaluation of existing data. In: H.E. Dregne (ed), Managing saline water for irrigation. Proc., Intl. Salinity Conf., Texas Tech Univ., Lubbock, TX. p. 187–198.

Appendix 17-1. Salt tolerances of various crops; compare yield response lines for various crops with the generalized zones of salinity tolerance shown in the key (adapted from Maas and Hoffman 1977).



Appendix 17-1, continued.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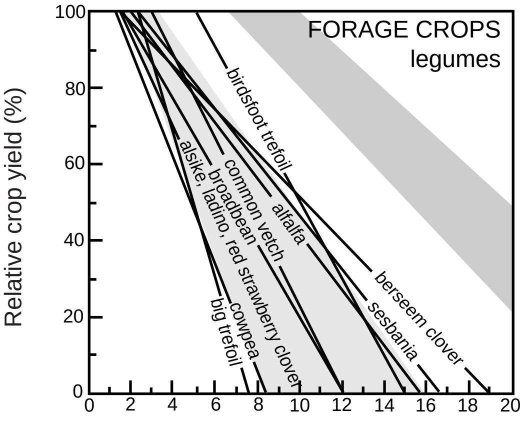
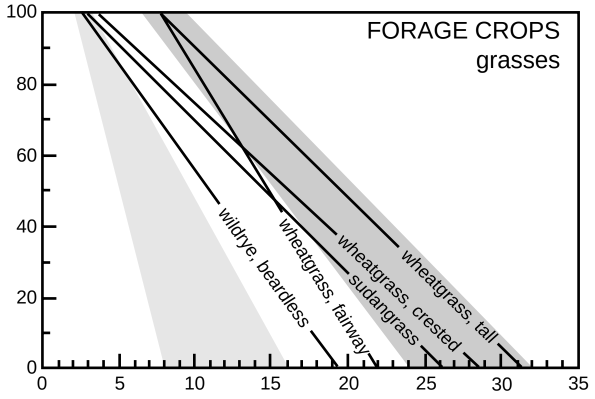
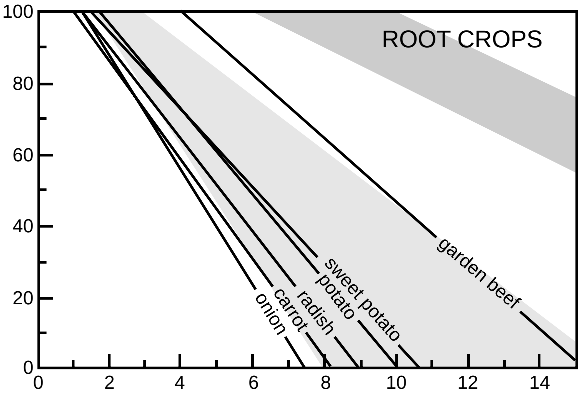
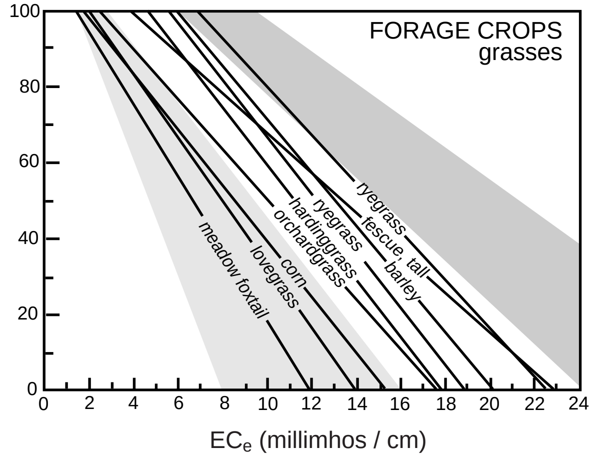
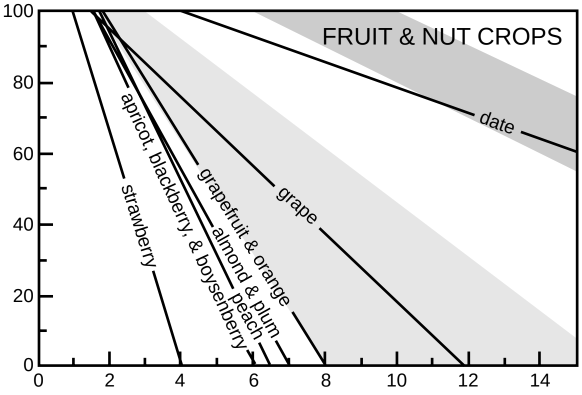
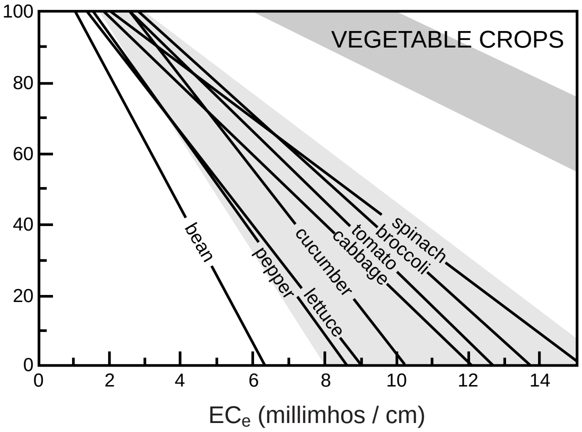

FORAGE CROPS legumes


FORAGE CROPS grasses


ROOT CROPS


FORAGE CROPS grasses


FRUIT & NUT CROPS


VEGETABLE CROPS