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SALINITY

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EYAL RONEN outlines the effects of salinity on soils and substrates, its impact on plant growth performance, and strategies to avoid it.

Introduction

Soil salinity is an increasing threat for agriculture and is a major factor in reducing plant productivity; therefore, it is necessary to better understand the reasons for its development and how to obtain sufficient control over the phenomenon. Salinity can be the result of both natural occurrence and human behavior.

Salinity problems occur in non-irrigated lands as a result of water losses through evaporation, transpiration, possibly salt input through rain, and seawater drift. Additionally, salinity can develop due to careless usage of several fertilizers, irrigation with saline water, or over-irrigation that causes capillary movement of hidden salts from lower layers in the soil, however, a much more extensive problem in agriculture is the accumulation of salts from irrigation water.

Evaporation and transpiration reduce the water content of soil by removing pure water as vapour. The water losses concentrate the solutes that are left behind in the soil solution. This concentration is sometimes referred to as ‘salt build-up’ and it may increase further when there is no opportunity to flush out and drain the accumulated salts. When the solutes in the active root zone reach a certain concentration, some changes take place in plant performance, especially in salt sensitive species, and plant injuries can be seen.

When there is a high concentration of Na^+ (Sodium) in soil, it is referred to as ‘Sodicity’. When Cl^- (Chloride) or other salts are involved, it is referred as ‘Salinity’.

How to measure salinity

A simple term is used to describe the measure of salinity of the soil solution or the irrigation water. The term ‘electrical conductivity’ (EC) is the most popular one, although salinity can also be described in terms of ‘osmotic potential’**.**

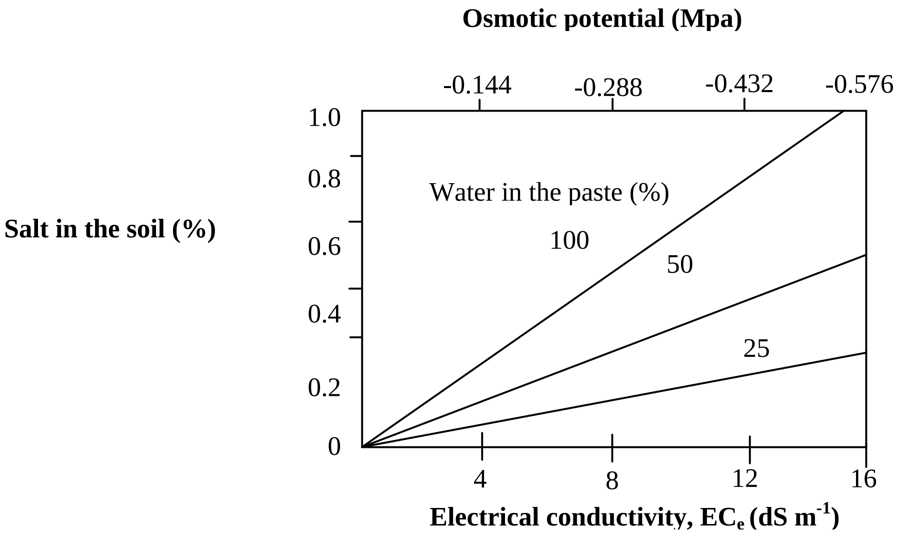
Pure water is a very poor conductor of an electric current. The conductivity is due to dissolved ions, which are also referred as electrolytes: the higher the salt concentration of the water, the greater its electrical conductivity and the lower its osmotic potential.

EC is measured in units of Deci-Simens/metre or Milli-Simens/cm units (mmho), and is affected by temperature. A standard measurement refers to 25°C. The osmotic potential of a saturated extract can be calculated from the EC - osmotic potential (Mpa) = EC ^{x} 0.036.

Table 1. Conversion factors relating to total dissolved salts or pure NaCl to an electrical conductivity (EC) of 1 Ds/m (1 deciSiemen/metre).

Measurement and units	**Application**	**1 Ds/m is equal to:**	**Equivalent units**
Conductivity (Ds/m)	Soils	1	1 Ds/m = 1 Ms/cm = 1 mmho/cm
Conductivity (µS/cm)	Irrigation and river water	1000 µS/cm	1 µS/cm = 1 µmho/cm
Total dissolved salts (mg/L)	Irrigation and river water	640 mg/L (approx.) or 530 – 900 depends on the salts	1 mg/L = 1 mg/kg = 1 ppm
Molarity of NaCl (Mm)	Laboratory	10 Mm	1 Mm = 1 mmol/L

__Figure 1. Relationship between the salt content of soil and the electrical conductivity (US salinity laboratory 1954).__



EC is measured in a saturated extract. Therefore, water content at field capacity, the salt concentration of the soil solution should be twice as high, and even much higher when soil moisture is below field capacity.

Table 2. Properties of seawater and good quality irrigation water.

Property	Seawater	Irrigation water
Concentration of ions (Mm)		
Na^+	457	<2.0
K^+	9.7	<1.0
Ca^{2+}	10	0.5 – 2.5
Mg^{2+}	56	0.25 – 1.0
Cl^-	536	<2.0
So_4^{2-}	28	0.25 – 2.5
HCO_3^-	2.3	<1.5
Osmotic potential (Mpa)	-2.4	-0.039
Total dissolved salts (ppm)	32000	500

The EC of the saturated extract may be misleading for two reasons. The EC at the root surface can be much higher than in the bulk soil, characterizing the total salt content but not its composition. The composition is very important. Generally speaking, within a certain EC range, 0 – 2.0 mS/cm, there is a difference in the impact on the plant between the ions that compose the EC. Some of the ions are beneficial to the plant and can be utilized by it, and some can be harmful and cause toxicity. The plant gains more from beneficial ions, nutrients, and although they also raise the EC, the benefit is compensating over this elevation. Above 2.0, whether the ions are highly demanded nutrients or less demanded ones, the impact of high EC is more crucial than any potential benefit.

Soil definition

Soils are considered saline if they contain salt in a concentration sufficient enough to interfere with the growth of most plant species, yet this definition is not referring to a fixed quantity of salt since it depends on soil texture, soil water capacity, plant specie, and the salt composition. The definition of saline soil level is not so clear and is more arbitrary. According to the US Salinity laboratory, saline soils are referred to as ones with EC greater than 4 mS/cm, equivalent to 40 Mm/l NaCl and an Exchangeable Sodium Percentage (ESP) of less than 15. These soils can appear in a wide range of pH, although they are normally natural with a slight tendency towards alkalinity. Soil which is affected by high sodium content, have higher pH (Sodic).

Differences between plants responses

Plant response to salt content may differ greatly. For each plant there is a salinity threshold point. Above this threshold, plant performance deteriorates and the yield is affected. The slope reflecting the rate of yield decrease is also important in the judgment of plant sensitivity. The sensitivity is a 'fluid' thing that may decrease or increase between cultivars within the same crop specie, change during different phenological stages, and is affected by environmental factors.

In the literature, several classifications exist that divide plants into groups according to their sensitivity to different levels of salt content. For example: Halophytes are a group where the growth is optimal at relatively high levels of NaCl. It is partially explained by their higher demand for sodium and/or chloride as mineral nutrients, and special mechanisms they have to avoid and tolerate the salinity. There is another group with moderate sensitivity, and Glycophytes**,** which have either low salt tolerance or high sensitivity and growth is severely inhibited.

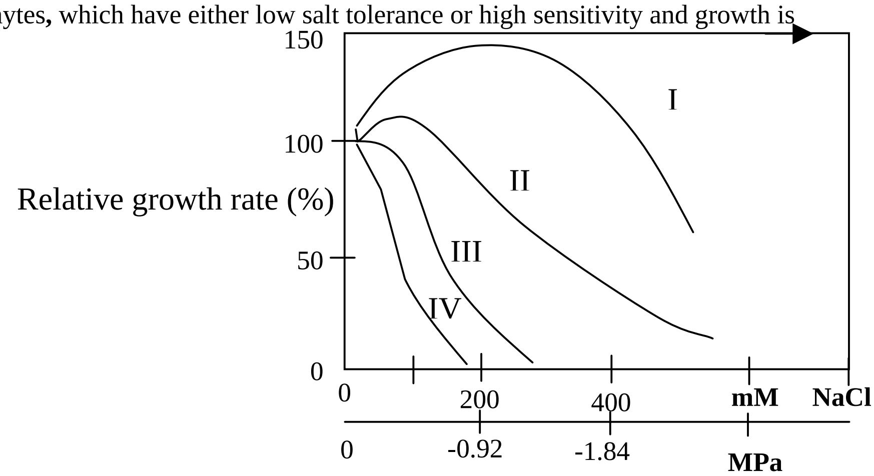


Figure 2. Growth response of various plant species to increasing substrate salinity and related osmotic potential.

I Halophytes
II Halophilic crop species
III Salt tolerant crop species
IV Salt sensitive crop species

The Riverside laboratory of California University in the USA has developed another known classification. The classification divides crops according to their response at different EC levels.

Table 3. 'Riverside' definition table of plant response to different electrical conductivity range.

E.C level (mS/cm)	Plant response
0 – 2	Influence on crop is negligible
2 – 4	Salinity restricts yield of highly sensitive crops
4 – 8	Most crop yields will be restricted
8 – 16	Resistant crops will manage.
16 and above	Only highly resistant crops will manage.

Salinity impact on plant growth performance

The salinity effect on the plant can be divided into three major effects:

- Water deficit – referred also as 'drought stress', resulting from the higher negative pressure at the root zone.
- Ion toxicity – resulting from the excessive uptake of less demanded elements, mainly Cl^- and Na^+.
- Nutrient imbalance – resulting from defected uptake, shoot transport or impaired distribution, mainly Ca^{2+}.

It is possible that not all constraints will appear, and even if they do appear their severity will not be the same. The impact on the plant may be affected by several factors, such as: ion concentration, relations with other ions, duration of exposure, plant specie, cultivar, root stock, phenological stage, plant organ, and environmental conditions.

Water deficit

Substrate salinity decreases the water availability due to high negative pressure that reduces the water uptake and the root pressure driven xylem transport. The substrate solution also contains dissolved nutrients, therefore, their uptake is affected as well. Decreased water uptake reduces the turgor of the leaf cells and thus inhibits the leaf elongation and the cell wall extensibility (*Lynch el al., 1988*). In saline substrates, both root and shoot growth are depressed, but as a rule shoot growth is more affected (*Termaat and Munns, 1986*). Root elongation is depressed by the presence of high concentrations of NaCl and the low Ca^{2+} concentrations (*Carmer et al., 1988*).

Ion toxicity and ion imbalance

Specific ions affect plant development when a relatively high concentration exceeds plant demand. Usually, the dominant ions that cause problems are Cl^- and Na^+, although sulfate salinization (Na_2SO_4) in some plants (*Sorghum*) can decrease growth similar to NaCl. Despite their essentiality - chloride as a micronutrient involved in the mechanism controlling the stomata aperture, and sodium as an essential mineral nutrient in Halophytes and some C_4 plants - for most plants these elements are more damaging than beneficial.

When these elements are taken up by the plants at high concentration, they accumulate in the tissue to the extent that they first cause chlorosis (yellowing and curl), and if the situation continues the tissue reaches necrosis**.** Necrosis is an irreversible situation - the tissue looses its vitality, turns brown, leaves curl and eventually the plant defoliates. It has been proved in many fruit trees that growth inhibition and foliage injury occur even at low NaCl salinization, which supports the notion that water deficit is not the constraint (*Sykes, 1992;Mass, 1993*).

Figure 3. Chloride toxicity symptoms in avocado leaves; sodium toxicity in banana leaves, and Chloride 'tip burn' symptoms in citrus leaves.

Ion toxicity mechanisms are believed to cause enzyme reactions, such as inhibition and inadequate compartmentation between cytoplasm and vacuoles. The Oertli (1968) hypothesis supports the explanation of salt accumulation in the leaf apoplasm leading to dehydration, turgor losses, and the death of leaf cell tissues.

Ion imbalance is caused by interactions between the uptake of different ions, where one ion affects the uptake, transport or utilization of another. The imbalance can be caused by antagonism and competition, or by chemical reactions that restrict the uptake of ions. Sulfate salinization can cause a depression in the shoot content for potassium and magnesium (Broursier and Lauchli, 1990). Sodium salinization is mainly related to low Ca^{2+} in the substrate, causing an imbalance in the tissue ratio for Na/Ca and displacement of Ca^{2+} from the plasma membrane root hairs (*Cramer et al., 1985*). In soil with high phosphorus availability, NaCl salinity may enhance phosphorus uptake and depress plant growth due to phosphorus toxicity (Roberts *et al.,* 1984). Chloride salinization may inhibit NO_3^- uptake.

Calcium disorders

High concentrations of Na^+ in the substrate inhibit uptake and transport of Ca^{2+} and, therefore, may induce calcium deficiency in plants growing in low Ca^{2+} concentration or high Na^+/Ca^{+2} ratios (*Lynch and Lauchili*).

Plants differ considerably in their sensitivity to Na^+ induced calcium deficiency. It has been suggested that high external Na^+ concentration may displace Ca^{2+} from the binding sites on the outer surface of the plasma membrane of root cells (Lynch *et al., 1987*). Inhibition of shoot elongation as mentioned is a result of several factors, among them the increase in the Na^+/Ca^{2+} in the leaf apoplasm (Rengel, 1992). In vegetable crops, soil salinity increases the incidence of calcium related physiological disorders like tip burn in lettuce and blossom end rot in tomato (Sonneveld and Ende, 1975).

The interactions of calcium and sodium are bidirectional and calcium was found to increase the salt tolerance of plants. Application of gypsum is a common practice in amelioration of saline-sodic soils. In addition to improving soil structure, it also increases salt tolerance. Gypsum has a dual effect: it improves soil structure and soil aeration, and increases the Ca^{2+}/Na^+ ratio, thus restricting Na^+ influx.

Table 4. Effect of salinization and Gypsum on the growth of Potato in sandy loam soil (Abdullah* et al., *1982).

Treatment	**Tuber yield (gr fresh weight per plant)**	
	Without gypsum	**With gypsum 2%**
Control (no salt)	221	226
0.6% salt	183	280
1.2% salt	149	207

Photosynthesis and respiration

Salinity has two major effects on photosynthesis:

- Leaf area is usually inversely related to salinity. Due to salt accumulation in leaves, tissue is damaged. The total effective surface of the leaf area decreases and no longer functions in the photosynthetic reaction. Salt is primarily accumulated in the mature leaves. Evaluation of the growth response to salinity is measured by the maximum salt concentration tolerated by fully expended leaves. Another evaluation of the salt threat can be done by comparing the rate of leaf death to the development of new leaves. If the rate of leaf death reaches the rate of new leaves, then the photosynthetic leaf area is too low to support continued growth (Munns and Termaat, 1986).
- Net CO_2 fixation per leaf area will decline, whereas respiration (during the dark) increases, leading to a drastic reduction in net CO_2 assimilation per unit of leaf area per day. A lower rate of CO_2 fixation during the light period is caused by water deficit, loss of turgor in the mesophyll, partial stomatal closure, and/or the effect of direct ion toxicity.

Salinity may increase the respiration rate of plant roots. High respiration consumes higher rates of carbohydrates for maintenance (Schwarz and Gale, 1981). The higher consumption is presumably the result of ion compartmentation, ion secretion (Na^+ -efflux pump), or the repair of cellular damage.

In a controlled environment, like in greenhouses, some techniques can be used to compensate and increase photosynthesis, and decrease the negative effect of salinity. CO_2 enrichment, which increases the carbon content in the atmosphere, is very important in saline conditions. It can overcome the limitations and increase salt tolerance markedly (Meiri and Plaut, 1985). Similarly, high irradiation may also increase salt tolerance (Helal and Mengel, 1981).

Protein synthesis

Protein synthesis in plant leaves decline, either in response to water deficit or to specific ion toxicity. The effects of NaCl salinity may result from both chloride toxicity in more sensitive species, and the imbalance created between Na^+/K^+ in more tolerant species. In some crops, replacement of K^+ by Na^+ is possible for osmotic adjustment, but not for protein synthesis. In some Halophytes, Na^+ can replace the potassium cations in protein synthesis (Gibson *et al.*, 1984).

In some cases, KCl fertilizers will decrease the effect of Na^+ due to the extra supply of potassium cations, although it may further decrease the osmotic potential of the soil solution.

Phytohormones

Plant response to salinity change some growth hormones, Cytokinin levels decrease, whereas levels of ABA (Abscisic acid) are increased (Kuiper *et al.*, 1990). Phytohormones production becomes inadequate due to impaired nutrient supply, uptake, or utilization.

Abscisic acid is important to plants for osmotic adjustment (Rosa *et al.*, 1985). The application of ABA may increase the salt tolerance by enhancing CO_2 fixation caused by the increase in PEP carboxylase activity (Amzallag *et al.*, 1990). It was reported through several works that the application of Cytokinins decrease leaf senescence caused by high salinity (Katz *et al.*, 1978).

Strategies to avoid salinity

Plants have developed two main strategies to overcome the effects of salinity. According to their response, plants can be divided into 'excluders' and 'includers'.

Exclusion – this mechanism avoids water deficit. Excluders balance the uptake of high concentration of solutes by enhanced synthesis of organic solutes (sugars, etc.). The mechanism is also involved with high retranslocation from the shoots to the roots, and the release of Na^+ and Cl^- from roots. In most crop species categorized as Glycophytes, exclusion is the predominant strategy. It means lower uptake and restriction of salts in comparison to includers. There is a possibility of differences in exclusion between Cl^- and Na^+ in the same plant, and between cultivars in the same specie.

Inclusion – this mechanism requires tolerance to a high content of Na^+ and Cl^-, or avoidance of high tissue concentration. The salt tolerance is based on inclusion and utilization of salts for turgor maintenance and replacement of K^+ by Na^+ in metabolic functions (sugar beet). This strategy involves partitioning Na^+ and Cl^- into different shoot organs. Partitioning occurs between young and mature leaves, leaf sheath and leaf blade, different cells in the leaf blade, and vegetative and reproductive organs. The compartmentation in mature leaves and avoidance in the young leaves is achieved by a general low xylem import of Na^+, and high phloem import of K^+ from the mature leaves (Wolf *et al.*, 1991).

There are many other strategies used for different crops, but this article is not aimed to extensively cover them all. A summary can be seen in the following graph.

Figure 4.

Plant responses

Excluder

Avoidance of internal water deficit:

- Enhanced synthesis of organic solutes.
- Decrease in surface area (succulence)

Includers

Tissue tolerance:

Salt compartmentation

- Synthesis of compatible solutes
- K^+/Na^+ replacement

Avoidance of high ion concentration

- Retranslocation in Phloem
- Increase in tissue water content (succulence).
- Salt excretion
- Leaf drop

Farm practices in case of salinity

It has to be stated that in reference to salinity, there might be a difference in sensitivity for the same plant at different growth stages. In general, plant sensitivity is higher in early stages of growth and decreases with plant maturity. In farm a practice, controlling the EC does not necessarily mean salinity can be kept low. In several situations, increasing the EC will be beneficial for the grower. In nursery stages, it is known practice to increase the EC in order to harden twigs for better 'germination' and better performance in soil in the later stages of growth. In several flower species, increasing the EC is a practice used to control the height of the stem according to marketing needs. In several vegetables and in particular cherry tomatoes, increasing the EC is a practice used to improve the quality of the fruit - increasing the TSS (Total Soluble Solutes) results in higher sugar content and sweeter fruits.

Controlling the EC can be done in two ways, either by water restriction or by fertilization of several highly soluble fertilizers. Restricting water will eventually lead to solutes concentrating in the soil solution due to water losses through evapo-transpiration. The same target can be achieved by using several fertilizers that have high solubility and contribute ions that are not in high demand, and therefore accumulate in the solution and increase the electrical conductivity.

A typical fertilizer commonly used for this practice is Kcl, potassium chloride, known also as Muriate of Potash (MOP). In most situations, MOP creates a major concern because of its chloride ions (cl^-). Potassium chloride contributes a huge quantity of chloride anions - for every 1,000 grams of K_2O (1 unit), equivalent to 0.833 kg of K, a quantity of 755.11 ppm's of Cl^- is added. Chloride is a highly soluble component, therefore will always be present in the soil solution and will force an increase of the electrical conductivity of the solution. Every 355 grams of Chloride contributes 1.0 mS/cm.

Fertilization

When using fertilizers, growers should consider the unavoidable increase of the electrical conductivity. Fertilizers are salt based and composed of two parts: ions with a negative charge (anions), and ions with a positive charge (cations). When fertilizers are dissolved in or by water, they break down to ions. It is highly recommended to use those fertilizers that are based on almost complete plant nutrients with minimal addition of undesired or less required elements like chloride, sodium, etc.

Irrigation

As a result of irrigation with water containing soluble salts added or naturally present, the salt load is continually adding to the soil solution concentration. Soil salts have to be removed on an ongoing basis through maintenance leaching to prevent yield losses from a salinity build-up. Leaching considerations include: crop sensitivity to salinity, presence of a high water table, efficiency of the irrigation system being used, crop consumption, and drainage. When the build-up of soluble salts in a well-drained soil becomes or is expected to become excessive, applying more water than that needed by the crop for consumptive use can leach the salts.

The portion of water applied in order to pass through the root zone to control salts at a specific level is called the 'leaching fraction', sometimes referred as the 'leaching requirement'. The leaching requirement (LR) can be estimated from crop tolerance salinity, as defined by the electrical conductivity of a saturated paste extracted from the soil at which no yield loss occurs, EC*e*, and the salinity of the irrigation water, as defined by the electrical conductivity of the applied irrigation water, EC*iw*.

Several methods exist for estimating the leaching requirement, each with its own limitations and benefits. Here is an example of the basic equation:

Figure 5. Leaching fraction equation

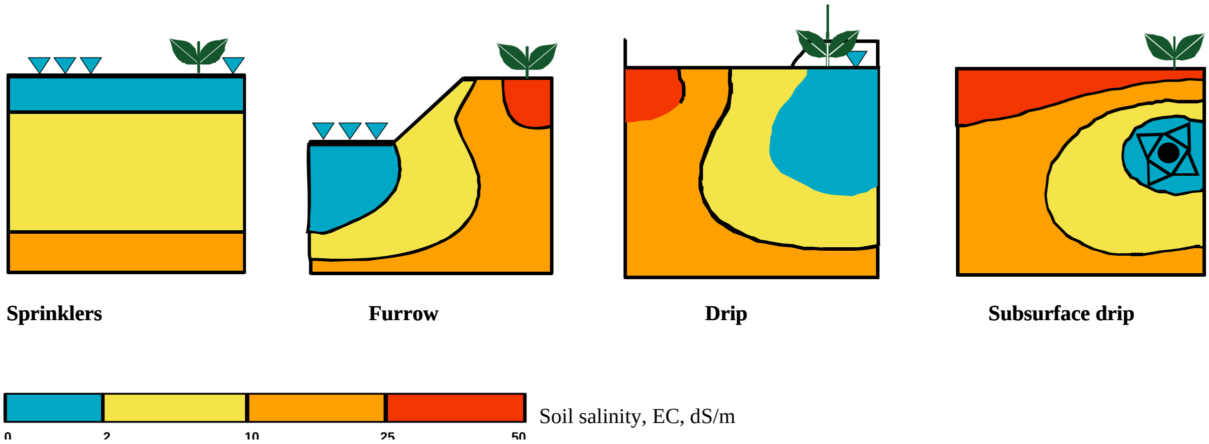
$$\mathrm{LF} = \frac{\mathrm{EC}_{iw}}{\mathrm{EC}_{e}}$$

Figure 5. Applied water equation

$$\mathrm{AW} = \frac{\mathrm{ET}}{1 - \mathrm{LF}}$$

We have to consider that different irrigation methods force different patterns of salt accumulation, as follows:

Figure 5. Salt accumulation patterns in relation to irrigation methods.



When the above practice is not followed, it is recommended to flush two to three times fold the volume used per the regular single irrigation at the same time. The water should be followed by a certain reduced concentration of nitrogen fertilizer. The concentration should be a third to half of the regular nitrogen concentration used normally at this period of plant growth. This is important to assure minimum fluctuations from high concentration to very minimal after the water is flushed; another reason is related to the fact that nitrogen in the form of nitrate (NO_3^-) is a strong antagonist to chloride (Cl^-). Supplying a certain concentration of nitrogen when chloride is present in the irrigated water will assure that the uptake of chloride will be restricted.

The above practices concern only control over the more soluble ions. For those that are less soluble and might affect the soil structure, different procedures should be used. In case of sodic soils, the goal is to replace the sodium with calcium and then leach the sodium out.

If free lime is present in the soil, it can be dissolved by applying sulfur or sulfuric acid. Sulfur products reduce the pH, which dissolves the lime, thus freeing up the calcium. If calcium is not present, it should be added. The most common form of calcium used for this purpose is gypsum; although calcium chloride, which reacts more quickly, can also be used but it is usually more expensive. After distributing the calcium source on the soil surface, it should be mixed and wetted to ensure adequate moisture is present to dissolve it. The water will ensure sufficient displacement and leach the sodium beyond the root zone.

Summary

It has been shown that in most situations, salinity is not a desirable phenomenon, although in certain cultivation practices it can be used to manipulate plants to higher quality. There is no doubt that by increasing the EC from a certain point for each crop, it will result in production deterioration.

Fertilizers should be used carefully. Unfortunately, plant nutrients appear as salts and therefore force an addition to the total electrical conductivity, yet with correct fertilization methods, and the right fertilizers, no addition of undesired salts like sodium or chloride will be needed. Therefore, irrigation and EC should be carefully monitored.

Above all, using irrigation correctly and choosing the right fertilizers will be meaningless if no control is used to monitor the salt level or the osmotic pressure in the soil/medium solution.

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