Chapter 4
Soil and Nutrient Management Under Saline Conditions

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Abstract Salt-affected soils are common in arid and semiarid environment and in irrigated agriculture. Soil salts have detrimental adverse impacts on soil's physical, chemical, and biological properties. Plants grown on salt-affected soils usually suffer from water shortage and nutrient deficiencies rendering them to grow under drought, low fertility, salinity, and ions-specific toxicity stresses. Salt-affected soils are very vulnerable and susceptible to climate change and environmental stresses, therefore, proper and integrated management of agricultural inputs including soil and nutrients is crucial for developing a sustainable and efficient farming system. Integrated soil and plant nutrient management combines both 4R nutrient stewardship, which is defined as the application of the right source, right rate, right time, and right place of nutrient application and conservation practices and is considered the most appropriate strategy for developing a sustainable farming system in salt-affected soils. Soil and nutrient management of salt-affected soils includes both reclamation processes and adaption of best agricultural management practices such as leaching of salts, replacing exchangeable Na with exchangeable Ca, maintaining mulch cover on the soil surface to reducing evaporation and limiting the capillary rise of saline water from the water table, use appropriate leaching requirement, irrigation scheduling, method of irrigation, quality of irrigation water, salt-tolerant crop/variety, and bed shape. Organic amendments also improve soil structure and facilitate salt leaching.

Keywords Salinity · Soil management · Nutrient management · 4R nutrient stewardship

1 Introduction

Soil salinity is a common term referring to the accumulated soluble salts in the soil and/or to the relative increase in the exchangeable sodium compared to calcium and magnesium at the exchange sites of the soil. It is more accurate to refer to the

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soils affected by these salts as ‘salt-affected’ soils, which are further categorized and classified into saline soils, sodic soils, and saline-sodic soils (Table 1). The saline soils are characterized by high concentrations of soluble salts, sodic soils are characterized by a high percentage of sodium adsorption ratio (SAR), while the saline-sodic soils are characterized by high levels of both soluble salts and sodium.

The sources of Salts and Salinization Processes include (Havlin et al. 1999):

- Old geologic saline layers: Naturally occurring processes: salt lakes, Dead Sea
- Mineral weathering without leaching
- Rising water table infuses the root zone with salts:
  - Plant water uptake will move and accumulate salts near surface
  - Upward movement with capillary water from groundwater
- Irrigation with saline water—Irrigation salinity
- Improper Management of Irrigation and Fertilization.

Salt-affected soils are common and are a widely recognized problem in arid and semiarid environments and in irrigated agriculture and they have become the most severe problem facing the world agriculture production system (Rus and Guerrier 1994; Rusan et al. 2003). The scarcity of water resources in most countries of the arid and semiarid regions has led many farmers to use poor-quality water for irrigation. Considerable amounts of such marginal water are available and can be successfully used for irrigation under proper management (Rusan 2018). However, using such marginal water for irrigation became an additional cause for the salinization of soil in these countries. Moreover, soils developed under arid and semiarid conditions are generally low in organic matter, alkaline in reaction, mostly calcareous, and in many cases saline and/or sodic (Rusan et al. 2003). This makes these soils very vulnerable and susceptible to climate change and environmental stresses (Rusan 2018). Therefore, proper and integrated management of agricultural inputs including soil and nutrients under saline conditions is crucial for developing a sustainable and efficient farming system (Rusan 2011).

Soil salts have a detrimental adverse impact on soil’s physical, chemical, and biological properties (Rusan et al. 2003). High concentration of soluble salts can reduce the availability of soil water and nutrients and severely inhibits their uptake by the plant. Moreover, the high percentage of exchangeable soil sodium has a detrimental impact on the soil’s physical properties and causes soil dispersion. This leads

Table 1 Classification of salt-affected soils and their main properties (Havlin et al. 1999)

Classification	EC (dS/m)	Soil pH	SAR (% Exch. Na)	Physical conditions
Saline	>4	<8.5	<15	Normal
Sodic	<4	>8.5	>15	Poor
Saline-Sodic	>4	<8.5	>15	Normal

to poor soil structure, poor water permeability, and infiltration in the soil (Arunin and Pongwichian 2015).

Plants grown on salt-affected soils usually suffer from water shortage and nutrient deficiencies rendering them to grow under drought, low fertility, salinity, and ions-specific toxicity stresses (Rusan et al. 2003). This comprises the main damaging impact of salinity on plant growth. In addition, the accumulation of toxic levels of various ions within the plants, even when the total concentration of salts is low can be detrimental to plant growth. It has been reported that the damaging effects of salinity on plant growth happen through physiological water availability (Al Karaki 2000; Lloyd et al. 1987) and the accumulation of toxic levels of various ions within the plants (Ali et al. 1993). A linear decrease in tomato plant dry matter production and total water content was reported by Al-Rawahy et al. (1992) with increased salinity.

Excess salts reduce nutrient availability and cause nutrient deficiency. A high concentration of salts in the soil solution increases the ionic strength of the soil solution. This will lead to higher and strong interaction among nutrients which will lower nutrient availability, such as the interaction between Cl and NO_3, P and micronutrients (Fe, Zn, Mn), K and Ca and Mg (Rusan 2018; Rusan 2017a, 2017b).

Nutrient uptake is actually a function of ion or nutrient activity in the soil solution and not of its concentration, which can be demonstrated by the following relationships (Havlin et al. 1999) and as shown in Fig. 1:

$$a_i = \Upsilon_* C_i \tag{1}$$

$$\mu = 1/2 \sum_{i}^{n} C_i Z_i^2 \tag{2}$$

$$Log\gamma_i = -AZi^2\left[\frac{\sqrt{\mu}}{1+\sqrt{\mu}} - 0.3\mu\right] \tag{3}$$

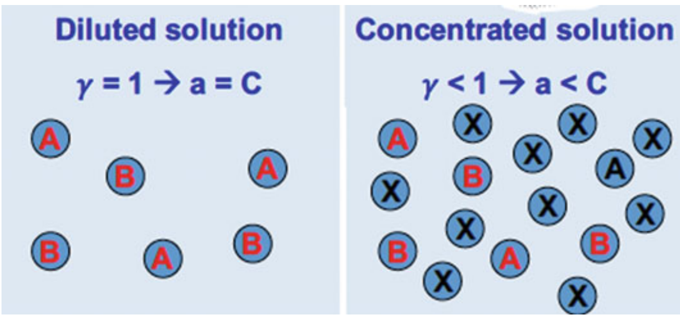


Fig. 1 Nutrient interaction in root zone

where a = activity; c = concentration; γ = activity coefficient; μ = ionic strength; z = ion charge; A = constant.

According to these relationships, the activity of the nutrient will be equal to its concentration only in diluted solution where the activity coefficient (γ) will equal one and thus a = c. Under normal field conditions, the soil solution will have some salts dissolved in it. The higher the salt concentration the lower the activity coefficient and thus the lower the availability of the nutrient to the plant.

However, plants differ in their tolerance to soil salinity, whereas tolerant crops have developed physiological and biochemical mechanisms for salt tolerance. Plants grown under saline conditions cope with salinity through several mechanisms, which have been proposed to improve salt tolerance in sensitive plants (Abdelrahman et al. 2005; Cano et al. 1996; Gisbert et al. 2000; Rus et al. 1999). These mechanisms involve the accumulation of solutes to balance osmotic adjustment and/or osmoprotection of intracellular components (osmotic adjustment and ion compartmentalization and/or biosynthesis of compatible solutes). These include betaine (Pan et al. 1991), free amino acids (Cano et al. 1996), soluble carbohydrates (Qaryouti 2001), and proline (Al Karaki et al. 1996; Huang et al. 2009; James et al. 2008). Osmotic adjustment in the cell lines occurred as a result of the accumulation of Na^+ and Cl^- with the maintenance of adequate intracellular levels of K^+. The maintenance of adequate intracellular K^+ levels is indicative that K^+ deficiency is not responsible for the inhibition of cell expansion and may indicate that membrane K^+ /Na^+ selectivity adaptations have occurred in the salt-adapted cells to facilitate K^+ uptake (Cramer et al. 1985). It is well documented that salt stress causes, at least in part, some of the cellular oxidative damage. Osmotic adjustment in the cell lines may occur as a result of the accumulation of Na^+ and Cl^- with the maintenance of adequate intracellular levels of K^+ (Rusan et al. 2003).

Tomato shoot and fruit physiological responses to salt stress conditions have been extensively investigated (Cruz et al. 1990; Mitchell et al. 1991; Niedziela et al. 1993). However, information on the effect of salinity on root growth is limited (Snapp and Shennan 1994). Studying the salinity effect on root growth and senescence in tomatoes, Snapp and Shennan stated that conventional observations of root length are not adequate and observing root system architecture should be considered. Root morphology parameters are important criteria for crop growth and responses to water and salt stress conditions. However, these parameters are often not determined due to difficulties associated with their measurements. Better methods for measuring root morphology parameters (root length, root surface area root diameter) are needed (Baker 1989). In this study, edge discrimination analysis using the desktop scanner was used to measure the root morphology (Pan et al. 1991). The objective of this study was to evaluate the root and shoot response of tomatoes to salt stress conditions under different levels of P nutrition.

Salt-affected soils are very vulnerable and susceptible to climate change and environmental stresses, therefore, proper and integrated management of agricultural inputs including soil and nutrients is crucial for developing a sustainable and efficient farming system (Rusan 2018). Integrated soil and plant nutrient management combines both 4R nutrient stewardship and conservation practices and is considered the most appropriate strategy for developing a sustainable farming system in salt-affected soils (Rusan 2018).

General requirements for soil and nutrient management of salt-affected soils include the following implementation of the reclamation processes and adaption of best agricultural management practices (Rusan 2017a, 2017b; Samuel et al. 1993):

- Leaching of soluble salts out of the root zone
- Replacing exchangeable Na with exchangeable Ca by adding gypsum (Gharaibeh et al. 2014)
- Maintaining mulch cover on soil surface to reduce evaporation and limit capillary rise of saline water from the water table
- In lowland areas, leveling the land to reduce ponding
- Use appropriate leaching requirements, irrigation scheduling, method of irrigation, quality of irrigation water, salt-tolerant crop/variety, bed shape
- Apply organic amendments to improve soil structure and facilitate salt leaching
- Supplying Ca and Mg to improve soil structure
- Adapt the 4R Nutrient Stewardship approach for nutrient management, that is apply the right source, rate, time, and placement of nutrient application (IPNI 2013)
- Phosphorus has been recognized to enhance root growth (Samuel et al. 1993) and it was found that plant root growth under drought conditions was stimulated by localizing the P fertilizers in the root zone (Rusan et al. 1998). This effect on root growth may enhance the performance of crops grown in saline conditions.

2 Management of Salt-Affected Soil

An integrated management approach should be adopted for sustainable management salt-affected soil. The approach includes both conservation practices and 4R nutrient stewardship to optimize effectiveness of the farming system (Fig. 2).

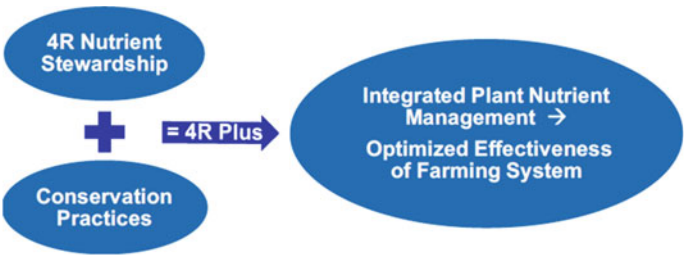


Fig. 2 Integrated management approach

Salt-affected soils can be managed by getting rid of the salt from the soil and leach them down from the soil profile (or at least from the root zone). This can be achieved through amelioration or reclamation of the salt-affected soil (Havlin et al. 1999). In the case of saline soil, this can be achieved through leaching the salts by application good quality water in an amount to leach the salt below the root zone. In case of the sodic soil and saline-sodic soil this can be achieved by fort replacing Na from the soil exchange sites with Ca by applying the gypsum ($CaSO_4$) and then leaching them with good quality water: Na-Soil + $CaSO_4$ → Ca-Soil + Na^+ + SO_4^{2-} (Havlin et al. 1999). If the soils are calcareous, then Na can be replaced by Ca by the application of elemental sulfur which will form $CaSO_4$ by reacting with the indigenous $CaCO_3$ as shown in the following reactions (Gharaibeh et al. 2014):

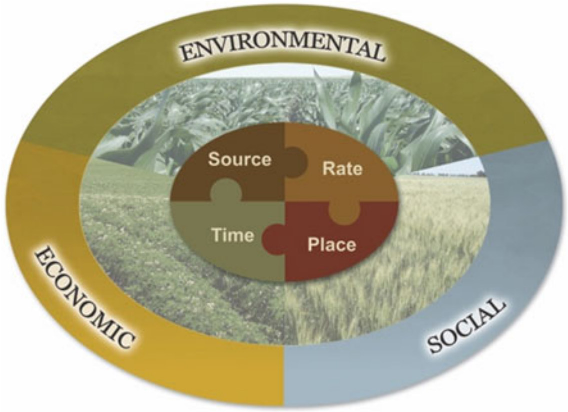
$$2S + 3O_2 + 2\,H_2O = 2\,H_2SO_4$$
$$CaCO_3 + H_2SO_4 = CaSO_4 + H_2O + CO_2$$
$$2\text{Na-Soil} + CaSO_4 \rightarrow \text{Ca-Soil} + Na_2SO_4$$

One should be careful not to leach or irrigate the saline-sodic soil with good quality water before getting rid of sodium as this will result in forming a sodic soil which will be more difficult to reclaim.

Another approach to manage salt-affected soils is to adopt the best agricultural management practices, which include soil management, nutrient management crop management, and nutrient management (Rusan 2018; IPNI 2013). The following practices are recommended for managing such soils (Havlin et al. 1999; Rusan 2017a, 2017b):

- Keep good soil structure with appropriate tillage and organic amendments
- Subsoiling and Deep tillage: Deep tillage interrupts capillary rise from groundwater
- Mulching: Cropping cover and Plastic cover (Picture 1)
- Phytoremediation: crops with shallow and deep roots, crops with high capacity to absorb salt
- Appropriate planting geometry and bed shape
- Salt accumulation depends on bed shape and irrigation method.
- Adaption of Integrated Plant Nutrient Management, which includes both the 4R Nutrient Stewardship approach and conservation practices (Rusan 2018; Rusan 2017a, 2017b; IPNI 2013).

Picture 1 Mulching by plastic cover



Picture 2 Logo of the 4R Nutrient stewardship

3 4R Nutrient Stewardship for Nutrient Management Under Saline Conditions

The 4R Nutrient Stewardship approach implies the application of nutrients using the right sources, at the right rate, at the right time, and in the right place and meets the goals of sustainability (IPNI 2013) (Picture 2).

3.1 *Selecting the Right Source of Nutrients Under Saline Conditions*

Selecting the right source of nutrients under saline conditions should consider the following: Firstly, one should use fertilizers with low salt index: (Table 2).

- Use of slow-release fertilizers → has a lower salt effect

Table 2 Salt index of fertilizers

Material and analysis	Salt index (sodium nitrate = 100)	
	Per equal weights of material	Per unit (lb) of plant nutrients
Nitrogen		
Ammonium nitrate, 34% N	105	3
Ammonium sulfate, 21.2% N	69	3.3
Calcium nitrate, comm. grade, 15.5% N	65	4.2
Sodium nitrate, 16.5% N	100	6.1
Urea, 46.6% N	75	1.6
Nitrate of Soda Potash, 15% N, 14% K_2O	92	3.2
Natural organic, 5% N	4	0.7
Phosphate		
Normal Superphosphate, 20% P_2O_5	8	0.4
Concentrated Superphosphate, 45% P_2O_5	10	0.2
Concentrated Superphosphate, 48% P_2O_5	10	0.2
Monoammonium phosphate, 12% N, 62% P_2O_5	30	0.4
Diammonium phosphate, 18% N, 46% P_2O_5	34	0.5
Potash		
Potassium chloride, 60% K_2O	116	1.9
Potassium nitrate 13% N, 46% K_2O	74	1.2
Potassium sulfate, 46% K_2O	46	0.9
Monopotassium Phosphate, 52% P_2O_5, 34%K_2O	8	0.1
Sulfate of potash-magnesia, 22% K_2O	43	2

Note N and K fertilizers have a higher salt index than P fertilizers, so salt damage is more likely when using these fertilizer formulations

- Use Organic Fertilizers
  - o Organic fertilization enhances soil fertility and OM:
  - o OM Mineralization releases humic substances, which:

    Improve soil phosphates and micronutrients availability due to acidification, chelation and
    prevent adsorption by coating calcite surface (Rusan et al. 2003)

  - o OM increases CEC which increases exchangeable-K^+, which is a competitor of Na^+, thus, preventing Na + into the exchange complex. Besides, K^+ is important to maintain turgor pressure of plants under salinity stress (Rusan et al. 2003; Rusan 2011; Rusan 2017a, 2017b)
  - o OM is a slow release of nutrients
  - o OM improves physical and microbiological properties of the soil
  - o OM supplies proline which enhances plant tolerance to salinity
  - o Growing legumes and using green manure has a similar effect as organic manure.
- Use Biofertilizers / Bioremediation. For example, the application of the Mycorrhizal inoculum will (Rusan 2018):
  - o Enhance plant survival stress condition
  - o Act as bioremediation and/or phytoremediation
  - o Enhance nutrient uptake efficiency by enhancing the plant to uptake nutrients from soil solution even when their concentrations are very low. This can be shown by decreasing the Cmin and Km which are the two parameters in the kinetic of nutrient absorption according to the Michalis and Menten equation (Fig. 3)
  - o Note that, Cmin refers to the minimum concentration below which no absorption, while Km refers to the concentration in the solution at 50% of the maximum velocity of absorption.

3.2 Selecting the Rate and Time of Nutrient Application Under Saline Conditions

It is important to apply the right rate of nutrient application to make sure the crop is receiving the required amount of nutrients, while avoiding excess. The right rate is necessary to avoid the application of excess fertilizer at one time which may cause salt damage, unnecessary fertilizer cost, reduce profitability and adverse impacts on natural resources, and accumulation of nutrients in agricultural products above acceptable levels.

Timing nutrient application when the nutrients are needed by the crop is critical to maximizing nutrient uptake and recovery efficiency and minimize nutrient losses

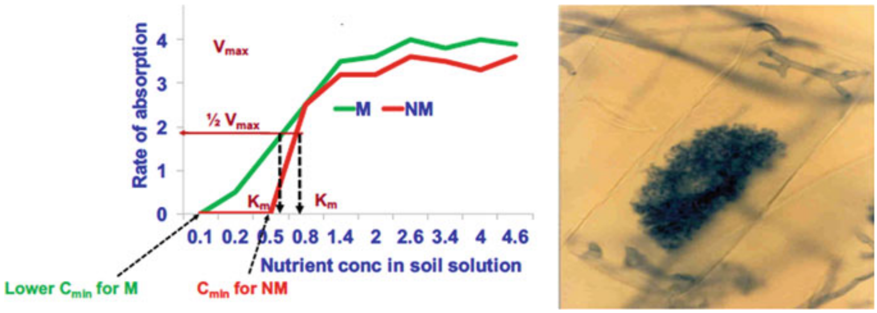


Fig. 3. Absorption of P from mycorrhizal and non-mycorrhizal plant under P-deficient soil (The photo, courtesy Rusan 2018, shows the arbuscular, which is a mycorrhizal organ developed inside the cell and acts as an exchange site for nutrients and assimilates between the host and the mycorrhizae) (Rusan 2003; Rusan 2017a, 2017b)

to the environment. Selecting the right time is a crop and site-specific management practice and depends on the local soil and climatic conditions, and on the type of crops and cropping system. For example, in coarse-textured soils, the nutrients are applied more frequently and in small doses to minimize losses by leaching. Phosphorus demand is high during the early growth stages and therefore, farmers should ensure the P is available during early growth stages. For most of the annual crops, highest nutrient uptake occurs during the flowering stage. For example, the highest uptake by a tomato crop occurs during the late vegetative and flowering stages. The uptake of nitrogen and potassium is initially slow, followed by a rapid increase during the flowering stage. Potassium uptake peaks during fruit development. The uptake rate of phosphorus and secondary nutrients (Ca and Mg) is relatively constant during the growing season for the tomato crop.

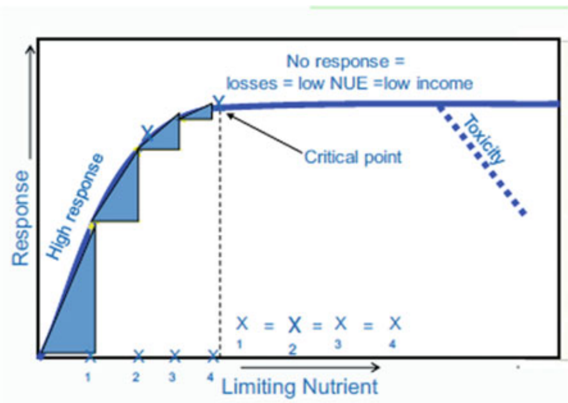
In general, the following should be considered when selecting the right rate and time of nutrient application.

- Consider Crop Characteristics and crop nutrient requirements for each growth stage
- Consider the rate that achieves the Maximum economic and ecological yield following the law of the diminishing return (Fig. 4)
- Consider the Right Frequency of Fertilization under irrigation, that is consider the right rate and right time of application of both water and nutrients (Rusan 2018). As shown in Fig. 5, if irrigation water was applied without fertilizer application, then the salinity level will remain about the EC of the irrigation water or 1 dS/m. If we fertigate in each irrigation, then the application of nutrients will raise the EC to 2 dS/m, and thus the EC in the root zone will be about 2 dS/m, or 4 dS/m if we fertigate on every second irrigation. In the following irrigation, there will be no fertilizer application and thus the EC would be the same as the EC of the irrigation water, which is 1 dS/m. In another case where the farmer needs to fertigate every 4th irrigation, then the fluctuation in the EC of the irrigation water and therefore the EC in the root zone will vary from 1 dS/m during the first three irrigation

events and 7 dS/m during the 4th irrigation event where the nutrient application rate will be 4 times more compared to the rate with every irrigation. It is well known that most crops grown under saline conditions tend to physiologically adjust to high levels of salinity (Physiological adjustment). However, in the case of low fertigation frequency such as fertigation with each 4th irrigation, the crops will be subjected to salt shocks by exposing them to very high salinity levels (7 dS/m). This will interrupt the process of physiological adjustment by, and cause salt damage to, the crop.

- Consider the right management of irrigation, that is select the right method of irrigation, the right quality of irrigation water (IW), the right irrigation scheduling/frequency, and the right leaching fraction. The salinity can be controlled by using the right leaching fraction (LF) (Samuel et al. 1993), which can be estimated for a particular crop using the LF equation:

Fig. 4. Law of the diminishing return



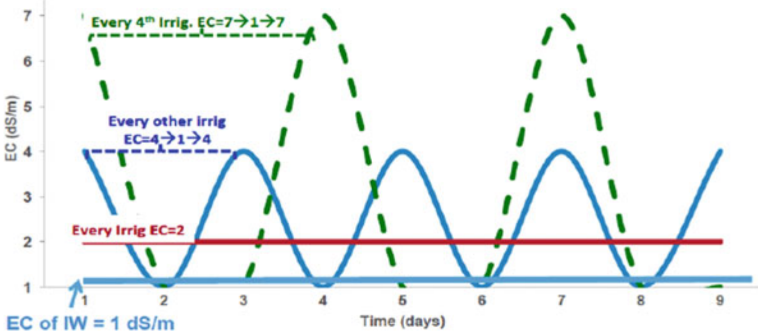


Fig. 5. Frequency of application of irrigation war and fertilizers under saline conditions (Rusan 2018)

$$LF = \frac{EC_w}{5(EC_e) - EC_w}$$

where;

LF = Min. LF needed to control salts within the crop tolerance (EC_e).
EC_w = Salinity of the IW in dS/m.
EC_e = Soil salinity of saturated extract tolerated by the crop.

Crop management under saline conditions should include the following:

- Select the salt-tolerant crops (species, varieties, cultivars)
- Select the crops with a high capacity to absorb and accumulate salts (Phytoremediation)
- Selecting the right plant geometry where growers should place the seeds or seedlings in the soil parts away from salt accumulation.
- Alternate planting deep and shallow root crops.

3.3 Selecting the Right Place for Nutrient Application

Proper placement of fertilizer has several benefits such as enhancing fertilizer use efficiency, reducing losses, enhancing seed germination and emergence, improving plant establishment, increasing yields, and improving the quality of crop production. Selecting the right place for fertilizer application plays a major role in enhancing the positional availability of the applied nutrients and in nutrient uptake. This is of more importance in the soil where the potentials for nutrient fixation, leaching, and volatilization are high. In fertigation, it is the wetted soil zone where the roots are most active and fertilizers must be placed within this small wetted soil volume to avoid being placed in dry soil and not available by plant roots.

Applied fertilizers are placed close to the roots, therefore, application of higher than recommended rates might induce a fertilizer burn and potentially inhibit root growth especially under saline conditions (Rusan 2018). Thus, one should consider placing the fertilizer at a rate not harmful to the root zone as such a zone is very small under drip irrigation, which is the common method of irrigation under saline conditions (Fig. 6). In other words, if the nutrient is located in a place where the roots cannot reach, or they are too far to be transported by mass flow, diffusion, or interception, then this nutrient is considered positionally not available and not bioavailable. This clearly illustrates the importance of the right place for fertilizer best management practices. In general, for selecting the right place for nutrient application growers should consider the method of irrigation, type, and geometry of the root system, soil physical and chemical properties, dynamic of nutrients in the soil, mechanisms of nutrient movement, and as well as the source, rate and time of nutrient application (Rusan 2018).

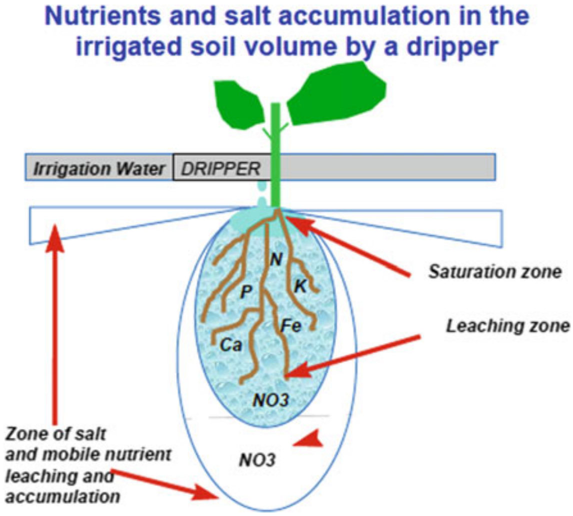


Fig. 6. Nutrient and salt accumulation in the irrigated soil volume by a dripper (Rusan 2018)

4 Conclusion

To properly and sustainably manage salt-affected soils and sustainable farming system, one should adopt the integrated management approach of agricultural inputs in particular the application of irrigation water and fertilizer. Such an approach will also integrate the 4R nutrient stewardship and conservation practices. The selection of the right source of irrigation water and of fertilizers in the right combination with the right selection of the right rate of application, and right time of application will ensure the sustainable management of salt-affected soils. Parallel to this approach, pressurized and localized irrigation methods should be adopted to minimize the negative impact of soil salinity. Such a method facilitates localized leaching of the salts from the root zone during the growing season, which is a practical approach to leach salt in areas of scarcity of water resources such as those that prevailed in the arid and semiarid regions. In the case of sodic soil, the replacement of exchangeable sodium with calcium is a prerequisite for the successful reclamation of sodic soil. To meet the main objective of farmers, it is highly recommended to grow salt-tolerant crops to ensure an acceptable level of income for the farmers. Since reclamation of salt-affected soils is in many cases expensive, the government should be involved either in subsidizing the farmers' plan for reclamation of their salt-affected soil or taking this task by itself.

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