Chapter 3
Salinity and Sodicity Adaptation and Mitigation Options

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Abstract Soil salinity and sodicity are twin constraints to agriculture production in many countries causing significant losses of crop production and land degradation. Once the salinity and sodicity problems are properly diagnosed, an integrated soil reclamation program may be formulated including combination of physical, chemical, hydrological and biological methods to rectify the twin problems. A combination of adaptation and mitigation technologies are to be adopted, for example adaptation allows the continued use of salt-affected soils by adjusting in response to the degree by which salinity and sodicity development has affected the soil, whereas, in contrast, mitigation refers to the technologies which are adopted to stop salinization to occur. It should be remembered that there is no single universal mitigation technology suitable for all soils, however, diagnostic based recommendations work satisfactorily for a specific site or location. Prior to setting up soil reclamation plan it is essential to review the available resources (farmer budget, availability and quality of water) and the objectives of reclamation and the reclamation plan established suiting the specific farmer needs. In this chapter, various soil reclamation methods such as; physical-leveling, subsoiling, mixing sand, seed bed preparation and salts scrapping); chemical (use of gypsum based on gypsum requirement, sulfur, acids etc.), hydrological-selection of suitable irrigation system-drip, sprinkler, bubbler, furrow, using the concept of leaching requiring/fraction to manage rootzone salinity, flushing, drainage, blending of water etc.; biological (use of organic amendments, green manuring, farm yard manures and selection of salt-tolerant crops) have be described. In addition, various methods of screening crops against salinity including hydroponics, field screening and serial biological concentration approach are described. Climate Smart Agriculture practices, integrated soil fertility management using **4 R** nutrient stewardship are concisely reported. Procedures of salt-harvesting from saline lands and deep deposits and their commercial exploitation in industries are also introduced.

Keywords Salinity · Sodicity · Adaptation · Mitigation · Soil reclamation · Leaching requirement · Salt harvesting

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1 Introduction

Soils affected by salinity and sodicity are not confined to just arid and semi-arid regions, where rainfall is insufficient to leach salts from the soil. Saline and sodic soils have been recorded in a wide range of environments under many different hydrological and physiographic conditions. Such a wide distribution tells us that '***no single adaptation or mitigation option or technique will be applicable to all land areas***'. However, diagnostics-based, site-specific recommendations can be viable options. Most importantly, they suggest the formulation of an integrated reclamation and management plan, one which is based on the major constraints facing us – available resources and variable environmental conditions.

First, one needs an integrated system of soil reclamation and management techniques, and these can generally be grouped into four adaptation or mitigation approaches to deal with salt-affected soils. The four approaches are: (i) Hydrological, (ii) Physical, (iii) Chemical, and (iv) Biological, though under unique environmental conditions salt-affected soils may be used for other purposes.

2 Mitigation and Adaptation Options

Mitigation and adaptation are terms commonly used in the context of climate change and many scientists believe that mitigation is primarily concerned with emission of greenhouse gases (GHGs), while adaptation deals with water and agriculture. However, mitigation and adaptation also apply to how mankind must deal with salt-affected soils. In this chapter, we have defined both terms in the context of salt-affected soils and their reclamation and management.

Adaptation allows the continued use of salt-affected soils by making adjustments in response to the degree by which salinity and sodicity development has affected the soil. In contrast, mitigation refers to the technologies which are adopted to stop salinization to occur.

3 Diagnostics of the Soil Salinity Problem

Soil salinity in agricultural fields is increasing worldwide, mainly due to poor farm management practices and the increasing demand for intensification of agriculture for the short-term benefits of increased food production. This intensification ignores the long-term consequences on 'other services' provided by the soil. It is, therefore, very important to understand the salinity hazard, both spatially and temporally at the regional and national farm levels.

In agricultural fields, an effective measurement of salinity will identify the location and extent of root-zone salinity and ensure that root-zone salinity is kept below the threshold level for each crop. Soil salinity is dynamic and has a wide variation vertically, horizontally, and temporally. Many consider soil salinity a uniform feature in a soil profile. However, Shahid et al. (2009) showed that, for the saline-sodic soils of Pakistan, salinity was a layered feature as one moved down the profile.

At the regional (Middle East) and national (Kuwait, United Arab Emirates) levels, a salinity mapping program (Shahid et al. 2010) helped policy makers in taking necessary and timely actions to tackle the issue of increased soil salinity. Similar programs will help to avoid a further spread of soil salinity to new regions; and they, if prove successful, will prevent negative impacts on national economies through degrading a nation's soil resources.

4 Integrated Soil Reclamation Program (ISRP)

Salt-affected soils are distributed across a wide range of hydrological and physiographical conditions, soil types, rainfall and irrigation regimes, as well as different socioeconomic settings. This diversity makes one realize that there will be no single technique of soil reclamation applicable to all areas. The exploitation of these soils for agriculture will require an integrated reclamation and management plan based on a comprehensive investigation of soil characteristics, including water monitoring (rainfall, irrigation and soil water-table), a survey of crops and local conditions, including climate, the economic, social, political, and cultural environment, as well as the existing farming systems. Fortunately, several approaches can be combined into an integrated system of soil reclamation and management (Shahid and Alshankiti 2013).

4.1 Objectives of Salinity Reclamation

The main objectives of reclamation are to:

- Improve soil health for better crop production
- Bring abandoned farms back to cultivation
- Increase the crop yield per unit of land area
- Improve food security within national boundaries
- Enhance water and fertilizer use efficiencies
- Optimize cost of crop production per unit area, and
- Improve the livelihood of the farmers

4.2 Prerequisite for Soil Reclamation

A soil reclamation plan can only be implemented if certain prerequisites are fulfilled. Some of these are essential for efficient, effective and long-term reclamation of salt-affected soils, as listed below.

- The farmer is convinced and ready to initiate soil reclamation at his farm
- The farmer has sufficient financial resources to implement the plan
- It is essential to have land leveling by laser before the initiation of any reclamation plan; this will help to ensure uniform water distribution and effective leaching of salts
- Additionally, a supply of good quality water is required
- Good subsurface drainage of the soil to be reclaimed is essential
- There must be a plan to handle drainage water safely, without compromising the environment

Sustainable agriculture with salt-affected lands is most likely to be achieved through integrated soil reclamation program (ISRP) and natural resource management (NRM). These are approaches where the long-term condition of the resource is built in as a core consideration. Thus, crop production on salt-affected lands can only be successful if the soil is dealt with in a holistic manner, i.e. in an '*integrated approach*' which includes all aspects of soil, water, plants and climatic conditions. There is, unfortunately, a misconception about ***Biosaline Agriculture***, that this is a complete solution for using salt-affected lands and saline and saline-sodic waters. Rather, biosaline agriculture is just one of the components of ISRP, which also includes physical, chemical, hydrological and biological methods (Box. 3.1).

Box 3.1 – Integrated Soil Reclamation Program (ISRP)

It should be noted that no single approach can deliver a complete solution to fix/reclaim soil salinity problem. This means that we need to take holistic approach by using a combination of mitigation approaches, which could be site-specific, and should only be used in other areas where similar soils and environmental conditions exist. International Center for Biosaline Agriculture (ICBA), Dubai, UAE has sufficient expertise in the diagnostics of the problem, developing an integrated reclamation strategy and implementation of this strategy to transform marginal soils to good quality for crop production, using methods, such as ***physical*** (leveling, salt scraping, tillage, subsoiling and sanding); ***chemical*** (use of soil amendments such as elemental S, acids, gypsum, etc. based on gypsum requirements to rectify soil sodicity problems and to improve soil health); ***hydrological*** (irrigation systems: Surface, flood, basin, drip, sprinkler, subsurface irrigation, etc., and leaching and drainage), and ***biological*** (biosaline agriculture: Salt tolerant crops, and a serial biological concentration approach). (Adapted from Shahid and Rahman (2011) and Shahid et al. (2011))

It should be further noted that the exploitation of salt tolerant crops and saline waters, i.e. '***Biosaline Agriculture***', without adopting other components of integrated soil reclamation, will ultimately degrade the soils further. These degraded soils will likely be unable to provide essential soil services, as such, but not limited to, agricultural production.

As discussed briefly above, recently established worldwide strategies for soil reclamation can be grouped into the following approaches which cover almost all aspects of soil reclamation and management.

- Physical
- Chemical
- Hydrological
- Biological
- Alternative land uses

4.3 Physical Methods of Soil Reclamation

There are several physical methods of soil reclamation, though not all of these methods are required for a given situation. Site-specific diagnostics can allow one to select the most suitable method(s). The most commonly used physical methods of soil reclamation are listed below.

- Leveling
- Subsoiling – deep plowing and deep ripping
- Mixing sand with heavy textured soil – sanding
- Seed bed shaping to reduce salinity effects – tillage practices
- Physical removal of the surface salt crust – scraping salts

4.3.1 Leveling

Leveling of salt-affected lands prior to the implementation of a reclamation program is essential. This allows for a uniform water distribution, leading to effective leaching of salts. Unfortunately, the farmer usually accomplishes this task by plowing the field, followed by the use of a conventional planking tool. This practice usually leaves the land uneven, which means that when water is applied to the field in order to leach the salts, the water puddles in the depressions and heterogeneous conditions are formed. There exists a modern tool '*laser land leveling*' to level the land in highly effective manner. It is, thus, suggested that each farmer should contact the extension services department in order to access this modern tool, which will facilitate an effective initiation of the farmer's soil reclamation program. The leveling process, however, may compact the soil due to the use of heavy machinery. If this occurs, the leveling process should be followed by subsoiling or chiseling.

4.3.2 Subsoiling

The soils affected by sodicity are usually underlain by dense clay-sodic layer(s). These dense layers are created by the dispersion of clay particles in the highly sodic water. The dispersed clay particles move to the subsurface of the soil where they are lodged on the surfaces of the conducting soil pores, thus, blocking the pores and preventing further water movement. It is particularly important, then, to disrupt the dense layers deep in the soil in order to enhance permeability. This is especially important for reclaiming sodic soils after the addition of amendments such as gypsum, followed by watering the field. The addition of gypsum will enhance the removal of exchangeable sodium (which has already been exchanged by Ca^{2+}) into lower layers of the soil prior to finally moving into the main drainage system. In addition to dense sodic layers, the soils may be underlain by a plow layer or by other hard pans occurring during soil formation. These hard pans must be disrupted and broken in order to enhance drainage capacity, and to facilitate the soil reclamation process.

4.3.3 Sanding

If the soil to be reclaimed has heavy texture (i.e., a clay soil), the mixing of sand in an appropriate quantity can change the soil texture permanently; the soil becomes more permeable and is easier to reclaim. This practice also provides a favorable environment for plant growth compared to the original soil prior to sanding. Changing the soil texture is a difficult and costly task, though where sand is readily available, such as in a desert, this practice can be accomplished more easily.

A clay soil is considered to exist in an area when it has the percentages of primary soil particles, as: 10% sand, 20% silt, and 70% clay (Textural class: Clay). The clay soil is mixed with a known quantity of sand to develop the following percentages of soil particles: 60% sand, 15% silt, and 25% clay (Textural class: Sandy clay loam).

In this way, the original soil texture (Clay) is significantly changed to another soil texture (Sandy clay loam). Both soil textural classes can be located on the USDA soil textural triangle (Fig. 3.1).

The newly established texture, a sandy clay loam, has improved soil physical properties, e.g. an increased drainage capacity and infiltration rate. This leads to an enhanced soil reclamation process and results in a much better leaching of salts.

4.3.4 Scraping

Salt accumulation in an irrigated field is common. Salts accumulate at certain zones based on the irrigation system in use and soil bed shape. The readers are referred to Chap. 4 of this book for more information in this respect. To clarify the scraping practice in order to remove salts, a furrow irrigation system is selected (Plate 3.1);

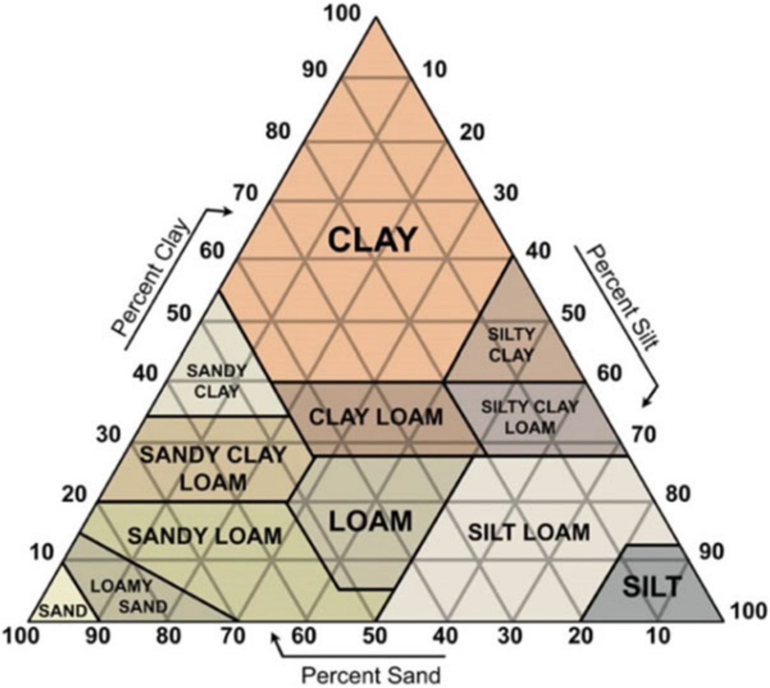

Fig. 3.1 USDA soil textural classes

Plate 3.1 Salts buildup in furrow irrigation system

both furrows are irrigated and the zone of salt accumulation appears in the center of the ridge. The salt crusts which accumulate at the surface, through capillary rise and subsequent evaporation, can be removed manually or through mechanical means. The mechanical removal is the simplest and the most economical way of reclaiming saline soils, if the area is small. This practice minimizes the salts temporarily; they will be accumulated again if there is a continuous feed of saline water to the soil surface. Therefore, the scraping method is considered a temporary solution.

4.3.5 Seed Bed Preparation – Tillage

Tillage can improve the soil's physical condition, and can bring a saline layer to the surface. However, it can also create a plow layer through the continuous use of the plow. Care must, thus, be exercised in using tillage. By manipulating the soil surface into different shapes and the selection of a specific irrigation system, a zone of low salinity can be achieved. It is well recognized that salts tend to accumulate on the ridges away from the wet zone when furrow irrigation is adopted. Placing the seeds on the off-center slope (i.e., shoulder) of the single row will position the seed in a location with a minimum salinity and an optimum moisture condition. Under high salinity conditions, the alternate row should be left un-irrigated. This will ensure maximum accumulation of salts in the un-irrigated area, thereby leaving the irrigated furrows free of salts and fit for planting seeds. The readers are referred to Chap. 4 for a detailed account.

4.4 Chemical Methods of Soil Reclamation

It should be kept in mind that chemical methods of reclamation are commonly used to reclaim sodic or saline-sodic soils. Saline soils are unable to be reclaimed by chemical methods. Chemical reclamation includes the use of gypsum, elemental sulfur and acids (hydrochloric and sulfuric acids), and the methods used are based on the diagnostics of the problem. Sodic soil can be recognized through visual assessment in the field, or through analyzing soils in the laboratory for exchangeable sodium percentage (ESP). A soil with ESP > 15 is classed as a sodic soil (USSL Staff 1954). At this threshold ESP value, the soil will show effects on both soil physical properties (structural damage) and also on plant growth. In such soils, the objective is to bring the soil ESP below the threshold value. This can be achieved by adding suitable amendments to increase the concentration of calcium ions (Ca^{2+}) in the soil.

4.4.1 Use of Gypsum to Reclaim Sodic Soil

The most suitable method is to replace exchangeable sodium with calcium, and the subsequent use of organic matter to bind the soil and improve its structure. Gypsum ($CaSO_4.2H_2O$) and lime (CaO) can both add calcium and, thus, can overcome dispersion as the calcium causes the inter particle forces to more readily hold the particles together. The calcium causes particles to form clusters (flocculates), forming a very clear puddle of water. Gypsum usually gives an immediate response as it dissolves (although it has low solubility) in water, though it leaches sooner than lime. Amendments are those materials which supply Ca^{2+} for the replacement of exchangeable sodium and furnish calcium indirectly by dissolving calcite ($CaCO_3$), which is naturally occurring in many arid zone soils. Gypsum is reported to reduce the levels of exchangeable sodium in the soil. It also improves both soil tilth and drainage, and achieves better crop production.

The addition of gypsum to a soil changes the soil chemistry in two ways: i) by increasing the amount of salt which is in solution, thereby avoiding the swelling and dispersion of the clay component. This is a short-term effect which occurs as the gypsum dissolves, and ii) the calcium from the gypsum replaces the exchangeable sodium which was adsorbed onto the clay at specific sites. This process changes sodic clay to a calcium-clay. The displaced sodium is then leached into lower soil zones, below the plant root-zone. Mined gypsum (less than 2 mm particle size) of commercial grade (~ 70% purity) is commonly used for the reclamation of sodic soils.

The following reaction occurs when gypsum is added to a Na-clay soil.

$$\underset{\text{Sodic soil}}{2Na^{+} - Clay} + \underset{\text{Gypsum}}{CaSO_4.2H_2O} \rightarrow \underset{\text{Normal soil}}{Ca^{2+} - Clay} + \underset{\text{Salts leach out}}{Na_2SO_4^{-} + 2H_2O}$$

4.4.1.1 Determination of Gypsum Requirement

Gypsum requirement (GR) is the quantity of gypsum needed per acre or per hectare of soil to lower the exchangeable sodium percentage (ESP) of the soil to a desired level.

4.4.1.2 How to Determine the Weight of One-Hectare Soil?

Laboratory methods for measuring gypsum requirement of a soil are based on meq 100 g^{-1} of dry soil. Thus, one needs to convert the GR in meq 100 g^{-1} to metric tons (weight) of soil present in a hectare at either 15 or 30 cm depth. The area covered by a hectare of land is 10,000 m^2 (100 m × 100 m). The weight of one-hectare soil of varying depths (15 or 30 cm) can be determined by the following procedure.

- First, determine the bulk density of soil by taking a cylindrical core (Plate 3.2) of soil with a known volume (e.g., a diameter of 8 cm, and a height of 5 cm).
- Remove the soil from the core and oven-dry it at 105 °C.
- Weigh the oven-dried soil (g).
- Determine the bulk density of the soil by using the standard calculation, as below:

$$\text{Bulk density} = \text{Mass of the soil(g)} \div \text{Volume of bulk soil collected} \left(cm^3\right)$$

Plate 3.2 Collection of a soil core to measure bulk density of the soil, and cleaning the core with a saw

Bulk volume is, thus, defined as the volume of soil occupied both by mineral matter of the soil and the space between the mineral matter particles.

Example

- Standard core size (diameter 8 cm; height 5 cm)
- Core volume ($\pi r^2 h$)

  where $\pi = 3.143$, r = radius of the cylindrical core in cm; h = height of the core in cm.

  $= 3.143 \times 4 \times 4 \times 5 = 251.44\ \text{cm}^3$
- Weight of the oven-dry sandy soil from the core = 402.4 g
- Bulk density of sandy soil = mass per unit bulk volume = $402.4 \div 251.44 = 1.60$ gram per cubic centimeter (g cm^{-3})
- Volume of one-hectare to a 30 cm depth (length × width × depth)

  $10{,}000\ \text{cm} \times 10{,}000\ \text{cm} \times 30\ \text{cm} = 3{,}000{,}000{,}000\ \text{cm}^3$
- Weight of 1 cm^3 of soil (1.60 g)
- Weight of 3,000,000,000 cm^3 soil = 4,800,000,000 g or 4,800,000 kg
- Thus, there are 4.8 million kilograms in a one-hectare volume of soil to the 30 cm depth, and 2.4 million kilograms to the 15 cm depth. In order to know if the soil needs the application of gypsum for reclamation, it is necessary to first diagnose the problem through field investigation (Plate 3.3). Once the soil sodicity is diagnosed, soil samples must be collected at different soil depths in order to assess the average level of sodicity. Then, the gypsum requirement can be calculated for sodicity reclamation.

4.4.1.3 Conversion of Gypsum Requirement – Lab Results to Field Application

Normally, the gypsum requirement (GR), determined through lab procedure, is in milli equivalent per 100 g of soil (meq 100 g^{-1}), which needs to be calculated as

Plate 3.3 On-site diagnosis of a saline-sodic soil in Pakistan, and sharing the experience with farmers

metric tons per hectare for 15 or 30 cm soil depth for the purpose of field application. The factor for conversion of the gypsum requirement values from meq 100 g^{-1} to tons per hectare is explained here. Based on the bulk density (1.60 g cm^{-3}) of the soil in the above example (UAE sandy soil average bulk density), 4.8 million kilograms weight of soil was determined to be present in one hectare area of soil to a 30 cm depth. Using these figures, a factor of 2.066 has been determined to convert the GR of 1 meq 100 g^{-1} soil to metric tons per hectare of soil to the 15 cm depth, and a factor of 4.132 to a 30 cm depth.

The USSL Staff (1954) has reported a factor of 0.86 to convert gypsum requirement (GR) from 1 meq 100 g^{-1} soil to tons per acre at a 15 cm depth. Since one hectare is equal to 2.471 acres, a factor of 2.125 is used in USDA Handbook 60 to convert GR from 1 meq 100 g^{-1} to tons per hectare at the 15 cm depth, and a factor of 4.250 for tons per hectare to a 30 cm depth.

4.4.1.4 A Comparison of Gypsum Requirement Between USSL Staff (1954) and Sandy Soils of United Arab Emirates

Assume we have analyzed five soils (A, B, C, D and E) for their gypsum requirement. These five soils have shown a GR of 1, 2, 3, 4 and 5 meq 100 g^{-1}, respectively. Calculate the GR of these five soils in terms of tons per hectare to the 15 and 30 cm depths using the above conversion factors. The calculated GR for the five soils is presented in Table 3.1.

It should be noted that the use of the GR conversion factor from the USSL Staff (1954) publication will slightly overestimate the GR (e.g, 4.250 tons per hectare versus 4.132 tons per hectare to the 30 cm depth for soil A). Therefore, it is advisable that countries where the bulk density of the soils is very different to that of most US soils, a new factor should be determined for each of the local soils.

Table 3.1 Gypsum requirement of five soils determined in lab and calculated in tons per hectare using conversion factors

	Soil gypsum requirement				
		Metric tons hectare^{-1} (USSL Staff 1954)		Metric tons hectare^{-1} (UAE soils)	
Soil	meq 100 g^{-1} (Lab results)	15 cm depth	30 cm depth	15 cm depth	30 cm depth
A	1	2.125	4.250	2.066	4.132
B	2	4.250	8.500	4.132	8.264
C	3	6.375	12.750	6.198	12.396
D	4	8.500	17.000	8.264	16.528
E	5	10.625	21.250	10.330	20.660

4.4.1.5 Gypsum Requirement

Method 1 (Schoonover 1952)

The procedure is described as follows.

- 5 g soil + 100 ml gypsum saturated solution (GSS) → 5 m of shaking in the mechanical shaker → filter and titrate for $Ca^{2+} + Mg^{2+}$ (in meq l^{-1})
- GR meq 100 g^{-1} = ($Ca^{2+} + Mg^{2+}$ meq l^{-1} in GSS) – ($Ca^{2+} + Mg^{2+}$ meq l^{-1} in filtrate) x 2
- Note that a factor of 2 is used to convert GR from meq l^{-1} to meq 100 g^{-1} of soil; derivation of this factor of 2 is explained below.
- Assume the GR is determined as x meq l^{-1}, then
  - 1000 ml of soil solution requires the GR = x meq
  - 100 ml of soil solution requires GR = $(x/1000) \times 100 = x/10$ meq
  - Or, 5 g of soil requires GR = x/10 meq
  - 100 g of soil requires GR = $x/10 \times 1/5 \times 100 = 2x$ (Note: Factor of 2 only works when 5 g soil is used in 100 ml GSS, different factors exist for different soil quanity).
- Assuming that the GR of a sodic soil is 1 meq 100 g^{-1} of soil, we need to determine how many metric tons of gypsum should be added to soil per hectare for each of the 15 and 30 cm depths.
- Equivalent weight of gypsum ($CaSO_4.2H_2O$) = 86.09 g
  - 1 equivalent of Na^+ will require 86.06 g of gypsum.
  - 1 meq of Na^+ will require 0.08606 g of gypsum.
  - Weight of one-hectare soil is 4,800,000 kilograms to the 30 cm depth, when bulk density is 1.60 g per cm^3.
  - The GR is, thus, 4.132 metric tons per hectare to the 30 cm depth or 2.066 tons per hectare to the 15 cm depth.
  - 1 hectare = 2.471 acres

In the above procedure, an equivalent amount of soluble CO_3^{2-} and HCO_3^- are also precipitated; therefore, this method accounts for exchangeable sodium and also for soluble CO_3^{2-} and HCO_3^- in the soil.

The calculation, however, is based on 100% pure gypsum. Commercial grade gypsum purity is about 70%. Therefore, a factor based on purity must be calculated in order to correct the GR requirement for the commercial grade gypsum.

Method 2 (USSL Staff 1954, Modified by Shahid and Muhammed 1980)
In this method, the gypsum requirement is calculated based on the exchangeable sodium and cation exchange capacity values taken from the laboratory analyses.

Example 3.1
A soil was analyzed in an accredited laboratory and following results were obtained.

- Exchangeable sodium (ES) = 4 meq 100 g^{-1}
- Cation exchange capacity (CEC) = 10 meq 100 g^{-1}
- Exchangeable sodium percentage (ESP) = (ES/CEC) × 100
- Thus, ESP will be 40. In order to reduce ESP from 40 to 15 (threshold value), one would need to add gypsum equivalent to 2.5 meq 100 g^{-1} of exchangeable Na^+. Thus, as above:
- 1 equivalent of exchangeable Na^+ 100 g^{-1} soil will require 86.09 g of gypsum.
- 1 meq of exchangeable Na^+ 100 g^{-1} soil will require 0.08609 g of gypsum.

Calculate the gypsum requirement (metric tons per hectare for the 30 cm soil depth), keeping in mind that the weight of one-hectare dry soil is 4.8 million kilograms.

From Example 3.1, it was determined that soil with a bulk density of 1.60 g per cm^3, a factor of 4.132 can be used to convert the GR from meq per 100 grams to metric tons per hectare for the 30 cm depth. Therefore, a GR based on the 2.5 meq per 100 grams will be equal to 10.330 metric tons of gypsum per hectare. However, the conversion factor for commercial grade gypsum should be applied to the 10.330 metric tons value.

Example 3.2
A soil was analyzed in an accredited laboratory and following results were obtained.

- Exchangeable sodium (ES) = 2 meq 100 g^{-1}
- Cation exchange Capacity (CEC) = 5 meq 100 g^{-1}
- Exchangeable sodium percentage (ESP) = (ES/CEC) × 100
- Thus, ESP will be 40. In order to reduce ESP from 40 to 15 (threshold value), we need to add an amount of gypsum which is equivalent to 1.25 meq 100 g^{-1} of exchangeable Na^+
- 1 equivalent of exchangeable Na^+ 100 g^{-1} soil will require 86.09 g of gypsum
- 1 meq of exchangeable Na^+ 100 g^{-1} soil will require 0.08609 g of gypsum

Calculate gypsum requirement (metric tons per hectare for the 30 cm soil depth), keeping in mind that the weight of one-hectare dry soil is 4.8 million kilograms.

From the example above, it was determined that for a soil with a bulk density of 1.60 g per cm^3, a factor of 4.132 can be used to calculate (convert) the GR from meq per 100 grams to metric tons per hectare for the 30 cm depth. Therefore, the GR based on adding the 1.25 meq per100 grams of gypsum will be equal to 5.165 metric tons per hectare.

From above examples, we can conclude that even if two soils have same Exchangeable Sodium Percentage (ESP), the gypsum requirement can be significantly different.

It should be noted that in this procedure of determining GR, an equivalent amount of soluble CO_3^{2-} and HCO_3^- (meq 100 g^{-1}) must be added (taken into account) in order to properly calculate the total gypsum requirement. This is because a gypsum equivalent to CO_3^{2-} and HCO_3^- will be precipitated. This modification to USSL Staff (1954) method was made by Shahid and Muhammed (1980).

4.4.2 Use of Acids to Reclaim Calcareous-Sodic Soils

It should be noted that the use of acids is recommended for sodic soils which are also calcareous. The acids react with the calcium carbonates present in soil to mobilize calcium, which ultimately replaces exchangeable sodium in the soil, thereby reducing the ESP. The objectives of acids application are to:

- Mobilize calcium from calcium carbonates
- Replace exchangeable sodium with calcium
- Bring about a reduction in soil pH, thereby enhancing nutrient uptake, and
- Improve soil health in order to obtain a better crop production

Both sulfuric and hydrochloric acids react rapidly with soil lime, since they do not have to go through an oxidation process. However, they are highly corrosive, and dangerous to handle. Specialized equipment has recently become available to safely apply acid onto field soil, usually with irrigation water. The reaction of applied acids with naturally occurring soil $CaCO_3$ and exchangeable Na^+ is shown below.

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + CO_2 + H_2O$$

$$\underset{\text{Sodic soil}}{2Na^+ - Clay} + CaSO_4 \rightarrow \underset{\text{Normal soil}}{Ca^{2+} - Clay} + \underset{\text{Salts leach out}}{Na_2SO_4 \downarrow}$$

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$$

$$\underset{\text{Sodic soil}}{2Na^+ - Clay} + CaCl_2 \rightarrow \underset{\text{Normal soil}}{Ca^{2+} - Clay} + \underset{\text{Salts leach out}}{2NaCl \downarrow}$$

4.4.3 Use of Elemental Sulfur to Reclaim Calcareous-Sodic Soils

Elemental sulfur can also be used to reclaim calcareous-sodic soils with one condition – the sulfur must be completely oxidized. This occurs through biological

Table 3.2 Equivalent amount of various amendments for supplying Ca in terms of pure gypsum

Amendment	Ton(s) equivalent to 1 ton of 100% gypsum[a]
Gypsum ($CaSO_4.2H_2O$)	1.00
Calcium chloride ($CaCl_2.2H_2O$)	0.86
Calcium nitrate [$Ca(NO_3)_2.2H_2O$]	1.06
Press-mud (lime-sulfur, 9% Ca + 24% S)	0.78
Sulfuric acid (H_2SO_4)	0.61
Iron (Ferrous) sulfate ($FeSO_4.7H_2O$)	1.62
Ferric sulfate ([$Fe_2(SO_4)_3.9H_2O$]	1.09
Aluminum sulfate [$Al_2(SO_4)_3.18H_2O$]	1.29
Sulfur (S)[b]	0.19
Pyrites (FeS_2, 30% S)[b]	0.63
Limestone ($CaCO_3$)	0.58

Adapted from USSL Staff 1954

[a] The quantities are based on the use of 100 % pure materials. If the material is impure, necessary corrections must be made. For example, if the gypsum is a 70 % agricultural grade, the equivalent quantity which must be applied will be 1.43 tons

[b] 100% oxidation is assumed though, in practice, it does not happen

Partial source: Ayers and Westcot (1985)

oxidation of sulfur by *Thiobacillus thiooxidans*, although in sodic soils sulfur oxidation is a very slow process. The complete oxidation of sulfur results in formation of sulfuric acid.

$$2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4$$

The H_2SO_4 formed through biological oxidation of sulfur reacts rapidly with lime (as shown above) and proceeds to reclaim the sodic soils.

There is a significant financial outlay required from farmers when using chemical amendments in soil reclamation. It is, therefore, recommended that the benefit of any amendment should be tested first in field trials with regard to its cost, safety in use, and effectiveness in improving (reducing) soil sodicity and increasing crop production. The theoretical amounts of various amendments to supply an amount of Ca equivalent to 1 ton of gypsum are shown in Table 3.2.

A good example is seen from an experiment with vertisol from India; Sharma and Gupta (1986) observed a similar change in ESP (Table 3.3) due to the application of either gypsum or H_2SO_4. However, they reported that there was a low hydraulic conductivity and higher amounts of water dispersible clay in the case of H_2SO_4 application. This was caused by the Ca^{2+} being a stronger flocculent than the H^+ ion of Sulfuric acid.

Table 3.3 Effect of different amendments (applied @ 100% gypsum requirement) on physical and chemical properties of a sodic vertisol (Sharma and Gupta 1986)

	Soil characteristics				
Amendment	$pH_{1:2}$	EC ($dS\ m^{-1}$)	ESP	$HC_{sat}{}^{a}$ ($mm\ hr^{-1}$)	Water dispersible clay (%)
Control	8.8	9.80	65	0.06	37.2
Gypsum	7.9	0.72	14	4.77	8.0
Pyrites	8.0	0.31	20	1.64	32.4
H_2SO_4	7.5	0.18	14	2.98	30.4
$Al_2(SO_4)_3$	7.6	0.27	8	4.49	8.6
$FeSO_4$	7.9	0.85	21	1.59	33.7

[a] Saturated hydraulic conductivity

4.5 Hydrological Methods of Soil Reclamation

Hydrological methods generally include irrigation, leaching and flushing, and the drainage of the leached water. Blending of water to reduce its salinity and sodicity, and recycling the water can also be included under this topic.

The objectives of soil reclamation through hydrological methods are:

- Efficient use of irrigation water
- Leaching of salts into lower soil zones, below the root-zone
- Improvement of water quality
- Improvement of a waterlogged condition through drainage

In irrigated agriculture, the salts in soil can be removed in two ways:

- Leaching of salts into a soil zone below the root-zone and subsequent drainage of the leached water to a safe place, and
- Surface flushing of dissolved salts

The salt content within the root-zone is likely to be increased if the net downward movement of salts is less than the salt input from irrigation water. Therefore, the soil salt balance must be kept under control. Control of the salt balance is, thus, a function of irrigation water quality, the quantity of dissolved salts in the water, and the success of the soil drainage system.

4.5.1 Leaching

Soils rich in soluble salts can be reclaimed through dissolving of these salts and their successful leaching. This can be accomplished through flooding or ponding of water at the surface for saline soils. In general, the depth of soil leached is roughly equal to the depth of water infiltrated during leaching. In order to leach salts from a soil, an understanding about the leaching requirement (LR) concept is important. The LR is the calculated fraction (depth) or quantity of water that must pass through the root-zone in order to maintain the EC of the drainage water at or below a specified level. Some soil scientists are of the opinion that LR should be minimized to prevent raising the level of the groundwater table, and also to reduce the load placed on the drainage system (Mashali 1995). Recently established guidelines for successful and economic leaching methods are described hereunder.

4.5.1.1 Timing of Leaching Irrigation

Timing of leaching does not appear to be critical, provided crop salinity tolerance limit is not exceeded for extended periods of time, or occurs during a critical stage of plant growth. The leaching can even be accomplished at each irrigation event. However, in a soil with a low infiltration rate, and for crops which are sensitive to excess moisture in the root-zone, leaching at each irrigation event may not be possible or advisable. Few important points to consider are listed below.

- Leaching should be done when soil moisture is low and water-table level is deep; and leaching should precede the critical growing stage of the crop plant
- An optimal time for leaching would be during a period with a low evapotranspiration demand, at night, during high humidity and in cooler weather
- Leaching can also be done at the end of the cropping season
- Soil and tissue analysis can help determine both the need and timing of leaching

Sandy soils in a desert environment, such as Gulf Cooperation Council (GCC) countries and other similar environments are well drained. Therefore, leaching of salts by using irrigation water amounts in excess of evapotranspiration can maintain salts in the root-zone to a safe limit. However, one major problem for irrigated agriculture under hot desert conditions is the high amount of drainage water which must be managed safely and sustainably, without compromising the environment.

4.5.1.2 Leaching Requirement and Leaching Fraction

Quantity of water that must pass through the root-zone to maintain the EC level at or below a specified level defines the ‘leaching requirement’. The ‘leaching fraction’ is the fraction of irrigation water that passes through the root-zone, into lower soil zones.

4.5.1.3 Leaching Requirement for Surface Irrigation

In order to determine the leaching requirement, it is essential to have information about two parameters: (i) salinity of the irrigation water to be used (dS m^{-1}), and (ii) crop tolerance to salinity (ECe in dS m^{-1}). Using the equation of Rhoades (1974) and Rhoades and Merrill (1976), the leaching requirement can be calculated as:

$$\mathrm{LR} = \frac{\mathrm{ECiw}}{(5\mathrm{ECe} - \mathrm{ECiw})}$$

Where, ECiw is the salinity of the irrigation water (dS m^{-1}) and ECe is for a given crop's maximum yield potential. LR refers to the minimum leaching requirement that is necessary to control salts within the tolerance limit of the crop, when the crop is grown under an ordinary surface irrigation method.

4.5.1.4 Leaching Requirement for Drip Irrigation System

$$\mathrm{LR} = \frac{\mathrm{ECiw}}{2(\mathrm{Max\ EC})}$$

Where, ECiw is the EC of the irrigation water, and a factor of 2 is obtained from ECsw, which is equal to 2ECe.

Knowing the desired leaching requirement (LR) and evapotranspiration (ET) demand of the crop, the net water required for a crop can be calculated (Ayers and Westcot 1985), as below.

$$\text{Net water requirement} = \frac{\mathrm{ET}}{(1 - \mathrm{LR})}$$

Where, net water requirement = depth of applied water (mm year^{-1}), ET = total annual crop water demand (mm year^{-1}), and LR = leaching requirement expressed as a fraction (leaching fraction).

4.5.2 Flushing

Flushing is suitable for saline soils which have surface salt crusts – a common situation in arid and semi-arid areas, and where rainfall is insufficient to leach the salts. This practice flushes the salts from soil surface and the flushed saline water then enters the drainage system, which becomes concentrated with salts. Flushing of surface salts is possible where soils are of a heavy texture and ponding can be accomplished easily. Once the water is ponded for a time which is sufficient to dissolve the salt crust, the ponded water can be flushed from the field, thus removing the surface salts. The following procedure will allow for successful flushing of surface salts.

- A sufficient volume of good quality water is used to dissolve salts from the soil surface
- The soil must possess the ability to allow for surface ponding, e.g. its subsurface must have a heavy texture

- The field must be capable of flushing the dissolved salts. This can be accomplished either by forming breaks in the sides of the field so that the saline water will drain into adjacent channels. Alternatively, the ponded saline water can be removed by siphoning it, using long pipes, into adjacent channels
- There must be ways to safely reuse the drained water, or environmentally safe methods available for its disposal

5 Drainage and Drainage Systems

Drainage is the natural or artificial removal of surface and subsurface water. Land areas which have waterlogged soils, or have a high (shallow) water-table, will require removal of the water if crop production is an objective.

Why drainage?
There must be a strong justification for installing a drainage system, considering the following points.

- Drainage is required to lower water-table
- Drainage is needed to address waterlogging and to bring the land back into crop production
- Drainage is needed to minimize the upward movement of groundwater and to control the buildup of salts due to capillary rise of the groundwater
- Salinity management will be necessary to improve crop production

5.1 Agricultural Drainage Systems

An agricultural soil affected by high water-table requires a drainage system to improve crop production and/or to manage water supplies. There are two types of drainage systems; surface and subsurface.

Depending upon the site conditions, nature of the problem, available resources, different types of drainage systems can be used, these are:

- ***Surface drainage*** – to allow for the runoff of excess water before it enters the soil
- ***Subsurface drainage*** – to control the groundwater table at a lower (safer) depth, by using either open ditches and tile drains or perforated plastic pipes. Methods include passive mole drainage, and also vertical drainage (pumping water) when the deep soil horizons have an adequate hydraulic conductivity.

5.1.1 Surface Drainage – Natural Drainage

This is the cheapest and easy way of draining the water and is possible where the underlying layers are permeable and relief is adequate. However, these ideal conditions do not always exist in saline areas, and a drainage system will always be required there.

5.1.2 Subsurface Drainage

This is the most suited drainage system for irrigated agriculture. It aims at controlling groundwater level, as well as leaching excess salts from the plant root-zone in order to keep the salt balance in soil water below the crop threshold. There are two types of subsurface drainage systems, open ditches and closed drains.

Open drains are deep earth ditches where groundwater flows and is ultimately discharged to a safe place for further use.

Closed drains are pipe drains installed in the field. They collect water and discharge it into a sump whose outlet leads to lagoons or basins.

5.1.3 Tile Drainage System

Tile drainage is a very effective way of controlling water-table and reducing waterlogging in areas where the soil aquifer cannot be pumped. It involves the installation of slotted PVC pipe (or other material) at about 1 meter below the soil surface. Soil water enters the pipe through the slots and is carried to a central well (pit) where it can then be removed, either by pumping or via gravity drainage. Tile drainage can be very expensive.

In order to assure the sustainability of the tile drainage system, it is important to accomplish the following checks on a regular basis.

- Drill test bores at a number of sites on the field
- Monitor water levels in these bore holes on a regular basis
- Check water quality (salinity and sodicity) on a regular basis

5.1.4 Mole Drainage System

In the mole drainage system, subsurface circular channels are developed by use of a mole plow for drainage, functioning like pipes buried in the soil. The success of a mole drainage system depends on the soil properties. Soils with a heavy texture are ideal for mole drainage as they are less vulnerable to collapse. Water continuously enters the mole channels, and the channels usually remain stable for a long time. The mole drainage system is much cheaper than a tile drainage system, and is usually developed on a closely spaced basis, yielding effective drainage. The only drawback

Plate 3.4 Vertical drainage through installing tube well (an example from Pakistan); the poor quality groundwater is used to irrigate salt tolerant plants at the Biosaline Research Station of NIAB, Pakka Anna near Faisalabad. Gypsum stones are also seen which are used as amendment for mitigating the high SAR and RSC (Residual sodium carbonates) levels of the water

of this system is its shorter life time, relative to the tile drainage system. The mole system is ideal for managing surface water and can also be used to reclaim both saline and saline-sodic soils.

5.1.5 Vertical Drainage

Removing groundwater through pumping is the most effective method of lowering a high water-table (Plate 3.4). To be able to pump groundwater, there needs to be a pocket of very coarse sand or gravel (an aquifer) below the soil surface, into which a slotted pipe (a ‘well-point’ or ‘spear’) can be installed. Water drains into the pipes through the slots cut into it. The water is then pumped to the surface. These systems are also sometimes referred to as ‘bores’. Apart from salinity and water-table control, pumping groundwater can also provide extra water to supplement irrigation supplies (depending on the salinity of the groundwater). Pumping groundwater from shallow aquifers (< 25 m) is the most effective way to alleviate salinity effects near the surface. In Pakistan, many tube wells have been developed through SCARP (Salinity Control and Reclamation Project) to lower the water-table in waterlogged or shallow (high) water-table areas, and they have successfully helped manage soil salinization.

6 Salinity Control and Methods of Irrigation

In arid and semi-arid zones salinization is common due to an annual rainfall which is insufficient to leach salts. Because of this, there are limited quantities of good quality water and this necessitates the use of saline water in agriculture.

In order to address the soil salinization in irrigated agriculture fields, it is important to select a suitable irrigation system based on the soil conditions, water salinity level, crop type and available resources. The correct choice can allow a farmer to manage irrigation-induced soil salinization at an acceptable level, without invoking salinity hazards to the soil. The reader is referred to Chap. 4 of this book to learn more about the available irrigation systems and salt accumulation in the soil. Irrigation systems are, thus, only briefly described below.

6.1 Surface Irrigation

Application of water by gravity flow to the soil surface is termed as surface irrigation, which includes flood, basin, border, and furrow methods. Irrigation applied by these methods develops salinity zones in soil based on the frequency and amount of water applied in each irrigation cycle. At the end of each irrigation cycle, the soil dries out and salts are concentrated. This adversely affects plant growth. Increasing the frequency of irrigation can lower the salinity but it may also waste water. Alternative methods to improve the efficiency of water include the drip or sprinkler irrigation systems, whereas nuclear technique such as using neutron moisture probe (Chap. 6) offers the best solution to use water efficiently under saline conditions. The change from surface irrigation to more modern irrigation systems is costly and will require justification, as well as better crop adaptability. Under a surface irrigation system, leaching is usually used to keep the salinity controlled in the root-zone.

6.2 Basin Irrigation

In basin irrigation, bunds are created around the field to prevent the water flowing out, thus, confining the irrigation water to the target area. This method is commonly practiced for rice cultivation (rice grown by ponding) and for trees. In the United Arab Emirates and other countries, date palms are grown in small basins, with the tree being planted in the center of the basin. It should be kept in mind that the basin method is most suitable for sandy soils where water leaches down fairly quickly. However, if the crops or trees are sensitive to ponding water, this method should be avoided. In basin irrigation system, surface salinity is controlled, although at the subsurface wetting zone soil salinity will develop.

6.3 Furrow Irrigation

In the furrow irrigation method, small channels are created in the field to carry water to the plants. When the water enters to the furrows some water infiltrates into the soil, the amount being based on the soil texture, and this water also flows along the slope. Under such an irrigation system, the crop plant is grown on the furrow ridges. Development of a salinity zone in the furrow system depends upon the furrow to be irrigated. If all furrows are used for irrigation, the maximum salinity development is on the center-top of the furrow ridge. If alternate furrows are used, then the salinity development zone is on the opposite side of the ridge. These potential salinity zones should be avoided when planting the seeds.

6.4 Border Irrigation

When border irrigation is to be used, the land is divided into different parcels of land each of which is surrounded by bunds to confine the water. The water is applied to the soil through small water channels. This practice is very common in India and Pakistan, where governments have taken the initiative to line the water channels to prevent water from seepage into the soil. Root-zone salinity can be controlled by using excess irrigation water to leach salts into a soil zone below the roots. However, if the soil is fine textured, capillary rise after an irrigation event can develop a salt crust at the soil surface.

6.5 Sprinkler Irrigation

A sprinkler irrigation system is similar to rainfall, i.e. water is sprinkled on the soil surface. The sprinkler system requires pipes to be buried in the soil at specific depth and water enters to these pipes for irrigation. Sprinkler systems often allow efficient and economic use of water and reduce deep percolation losses. Chhabra (1996) is of the view that, if water application through sprinkler is in close agreement with crop needs (evapotranspiration and leaching), drainage and high water-table problems can be greatly reduced, which in turn should improve salinity control.

6.6 Drip Irrigation

The drip irrigation method is the most efficient among all modern irrigation methods. In this system, water is applied precisely to the plants on a daily basis to meet the water requirement of crops. Drip irrigation is also ideal for delivering nutrients to the root-zone, thus optimize nutrient use efficiency. Drip irrigation has a priority over sprinkler irrigation, as the latter may cause leaf burn, defoliation of sensitive species, which generally does not occur with drip irrigation. The system consists of plastic pipes with emitters at specific intervals which are based on the distance between the plants in the rows.

7 Biological Methods of Soil Reclamation

Biological methods of soil reclamation include the use of organic material(s) to improve soil structure and to mobilize calcium from calcium carbonates through the decomposition process. ***Biosaline Agriculture*** (growing salt tolerant crops) is also part of biological reclamation.

7.1 Use of Organic Amendments

The soils of the arid and semi-arid regions are generally deficient in organic matter where saline and sodic soils are commonly found. The dispersed sodium in soil degrades the soil structure and restricts root growth and water movement in soil. Under such conditions, it is essential to improve soil structure. The organic matter can be added in following ways.

- Mixing previous crop stubbles into the soil
- Addition of farm yard manure
- Addition of crop residues into the soil
- Use of mulch material(s)
- Growing of green manure crops, such as legumes

The addition of crop residues and other organic materials improves soil structure. The legume crops used for green manure, in addition to adding organic matter, also add nitrogen into the soil, thus providing a dual benefit. Development of soil structure prevents soil erosion and hastens soil reclamation, primarily due to increased infiltration. The decomposition of organic matter produces a high level of CO_2 and also increases organic acids (humic, fulvic), which lower the soil pH. These processes increase the solubility of calcium carbonate and mobilize calcium, thereby replacing exchangeable sodium from the soil exchange complex and reducing soil sodicity.

Organic amendments, when applied in conjunction with inorganic amendments, can be more effective (Dargan et al. 1976). Awan et al. (2015) reported that application of farm yard manure alone or in combination with inorganic N fertilizer has significant effect on wheat yield on saline-sodic soil both under monoculture and in agro-forestry systems. The selection of the organic matter to be applied is very important in order to avoid causing N deficiency (adding an amendment which has too high C:N ratio) and also increase salinity (e.g., cow dung slurry). Use of green manure crops may have a better chance than farm yard manure of being successfully integrated into a soil reclamation management package.

7.2 Biosaline Agriculture

Very few plant species grow well on saline soils, most either fail to grow or their growth is appreciably retarded. Salinization, thus, restricts options in choosing a successful crop species. Biosaline agriculture is the economic utilization of salt-affected soils for agricultural purposes, e.g. the growing of salt tolerant crops of agricultural significance. Biosaline agriculture includes the use of salty water for sustained agriculture. In the past, the term saline agriculture was used; however, a broader definition is now needed, one which includes the manipulation of desert and sea resources for both food and fuel (energy) production. For a successful adoption of biosaline agriculture, the following two points should be considered.

- Locations where biosaline agriculture is to be practiced must be studied carefully and potential problems diagnosed
- Based on the diagnostics results, one must choose appropriate measures for maximizing economic returns under each specific situation

Biosaline agriculture has a wide scope with diversified dimensions. These include:

- Breeding for salt tolerance within appropriate plant species
- Selection of salt tolerant genotypes, i.e. ‘cultivars’
- Domestication of salt tolerant plants for economically sound (but sustainable) exploitation of salt-affected lands
- Climate smart agricultural practices (land preparation, planting, irrigation and fertilization, etc.).

Plant physiological studies will identify physiological factors controlling yield under the marginally saline conditions, and utilize physiological differences between salt tolerant and salt sensitive genotypes with a view to developing selection criteria for salt tolerance.

7.3 Screening Methods

The screening of a range of crop varieties (cultivars) across different levels of salinities can be a useful way to begin moving toward biosaline agriculture. There are a number of screening methods and the best will closely simulate the conditions under which a crop variety will be grown. Techniques range from laboratory investigations of seed germination capabilities to glasshouse studies and field experiments, and are discussed in detail by Shahid (2002), and briefly below.

7.3.1 Screening in Greenhouse Using Hydroponics

The seeds of different crop cultivars are first germinated in small dishes, and at the 2–4 leaf stage, the plants are transferred to aerated Hoagland's solution by carefully placing them through small holes made in thermopol sheets (which float on the surface of the hydroponic culture solution). The salinity of culture solution is then increased stepwise, being maintained at a range of levels, e.g. 0, 100, 150, 300 mM NaCl, etc. The cultivars which survive at higher salt concentration undergo a preliminary selection, and are then subjected to further testing in both greenhouse and under field conditions.

7.3.2 Screening in the Field

Two field screening methods are commonly used.

In the first method, different varieties/cultivars of a crop are grown in lines. On one corner of the field, the sprinkler system is established with a non-saline, fresh water supply. In the other corner of the field, a sprinkler system is installed with a saline water supply. The water from both systems is sprinkled in different ratios through the use of special adjustments of the nozzles for different lines of the various cultivars. Plastic cups can be placed in each line of plants in order to collect samples of the 'mixed' water sprays for assessment of the salinity of water applied in the field. The shoot or whole plant dry matter and the grain yields are measured as a criterion of salt tolerance (Shahid 2002).

In the second method, different varieties/cultivars are grown in different lines. Each set of crop plants is irrigated through drip or sprinkler irrigation system with water of different salinities. As in the first method, grain and biomass yield can be used as a measure of salt tolerance of the differing crop varieties.

8 Serial Biological Concentration (SBC) Concept

The Serial Biological Concentration of Salts (SBCS) concept was introduced by Heuperman (1995). The SBC was developed as a multiple production system to utilize drainage water from irrigation schemes. In SBC, the drainage water of increasing salinity is collected and reapplied to 3 or more successive irrigation plots on which crops of known (different) salt tolerance are planted (Blackwell 2000; Cervinka et al. 1999). The SBC system involves the reuse of drainage water on progressively more salt tolerant crops. Each crop is underlain by a tile drain for the collection of water to be used to irrigate the next stage. Within the crop sequence, the drainage water collected is reduced in volume due to plant water use. Thus, the salinity of the drainage water increases since there will be little or no salt uptake by the plants. The final effluent water is contained in relatively small evaporation ponds. This makes it feasible to consider the use of a floor lining for the pond in order to eliminate leakage. These ‘salt water’ ponds could also be used for fish farming. The highly saline water can also be collected in a series of ponds where, through evaporation, the salts can be collected if they have commercial value, or need to be safely disposed off.

9 Genetic Engineering (Developing Salt Tolerant Cultivars)

Molecular biology and the use of appropriate methods of genetic engineering could also play a role in developing salt tolerant crop genotypes (varieties) which are resistant to marginal environments (drylands, saline lands) for food and/or biomass production. Shahid and Alshankiti (2013) has identified some researchable ideas (or areas) which could lead to solutions for meeting the food demand of the earth’s growing human population. Researchable ideas that may help meet the need for sustainable increases in crop production (Shahid and Alshankiti 2013) are listed below.

- Develop cultivars which have low water requirement, and ones with stomatal closure midday (to reduce transpiration)
- Introduce a Biological Nitrogen Fixation (BNF) character in non-leguminous crops to reduce dependence on commercial N fertilizer
- Enhance sunlight use efficiency for photosynthesis, thereby yielding increased dry matter production
- Introduce resistance to heat shock, salinity and water stress, thereby yielding more drought tolerant varieties, and
- Develop viable options to maximize yield under warmer (and water deficit) conditions through traditional breeding and agronomic research

10 Crop Yield Estimation Under Saline Conditions

Crop yields decrease as a factor of increasing soil salinity above a threshold salinity value. Crops can tolerate salinity up to a certain level (Maas 1990) without a measurable loss in yield, i.e. the ‘threshold salinity’. As a general rule, the more salt tolerant is the crop, the higher is the threshold salinity level. Crop yields are reduced in a linear manner as salinity increases above this threshold salinity, as shown in the equation.

$$\mathrm{Yr} = 100 - \mathrm{S}\ (\mathrm{ECe} - \mathrm{t})$$

Where, Yr is crop yield relative to the same conditions without salinity, t is the threshold salinity, S is the % linear rate of yield loss with a 1 ECe (dS m^{-1}) increase above the threshold value. ECe is the electrical conductivity of the soil saturation extract and represents the average root-zone salinity. The expected yield (Yr) of a crop grown at a specific level of salinity (ECe) can, thus, be calculated. The reader is referred to Chap. 4 of this book for further details.

11 Integrated Soil Fertility Management (ISFM)

In parallel to the management of salinity and sodicity in agriculture fields, it is equally important to keep the soils healthy and productive through the maintenance of an optimal soil fertility status. The soils of the arid and semi-arid regions of the world are inherently low in soil fertility. There is an ongoing need to replenish the soil's nutrients through strategic use of chemical fertilizers and organic manure (s) that will ensure sustainable yields. The ISFM is an effective strategy for sustainable agriculture.

The replenishment of soil nutrient pools, on farm recycling of nutrients, reducing nutrient losses and improving the efficiency of inputs on saline and sodic soils is much more important than on good quality non-saline soils. The ISFM combines the use of both organic and inorganic sources to increase crop yield, rebuild depleted soils and protect a wide range of natural resources. Organic amendments can increase the efficiency of inorganic fertilizers through positive interactions on soil biological, chemical and physical properties. The ISFM optimizes the effectiveness of fertilizer and organic inputs in crop production and its implementation can rehabilitate degraded soils and restore their sustainable productivity. To be successful in nutrient replenishment for sustainable crop production, a new **4R** strategy needs to be used.

11.1 What Is a Four Right (4R) Strategy?

The four R (4R) nutrient strategies should be used to offset the plant's nutrient requirement, which involves:

- Right type of chemical fertilizers – e.g., ammonium versus nitrate based fertilizers
- Right rate of fertilizer – based on soil testing and target yield
- Right time of fertilizer application at the right growth stage – apply each fertilizer when the plants need specific nutrients
- Right location of fertilizer application – apply to the root-zone area where the nutrient can best be absorbed by plants

The fertilizer use efficiency of nitrogen fertilizers under field conditions is assessed using isotopic techniques of nitrogen-15 (see Chapt. 6 for detailed information).

12 Conservation Agriculture (CA)

Conservation agriculture (CA) is part of Climate Smart Agriculture (CSA). CA recognizes the importance of the upper 0–20 cm of the soil as the most active zone, and also the zone most vulnerable to erosion and land degradation. By protecting this critical soil zone, we ensure the continuity of good agriculture and a good environment.

Main principles of conservation agriculture, discussed in Dumanski et al. (2006), are listed hereunder.

- Maintaining a permanent soil cover and making certain that there is a minimal mechanical disturbance of the soil through the use of zero tillage systems. This will help ensure sufficient living and/or residual biomass to enhance soil and water conservation and control soil erosion.
- Promoting a healthy, living soil through crop rotations, cover crops, and the use of integrated pest management technologies
- Promoting the application of appropriate fertilizers, pesticides, herbicides, and fungicides in a strategic way to maintain a sustainable balance with crop requirements
- Promoting precision placement of inputs to reduce farm costs, optimize efficiency of operations, and prevent environmental damage
- Promoting legume fallows (including herbaceous and tree fallows where suitable), composting and the use of manures and other organic soil amendments
- Promoting agro-forestry for fiber, fruit and medicinal purposes.

13 Climate Smart Agriculture (CSA)

Climate smart agriculture (CSA) includes proven practical techniques and approaches that can help achieve food security, adaptation to and mitigation of the effects of a changing climate. Increasing soil organic matter content and moisture through low to zero tillage and the use of mulching make crop yields more resilient and combat soil degradation. The introduction of integrated soil fertility management can also reduce chemical fertilizer costs.

CSA seeks to increase productivity in an environmentally and socially acceptable way, strengthen farmers' resilience to climate change, and reduce agriculture's contribution to climate change by reducing greenhouse gas emissions and increasing carbon sequestration and storage on farm land. Climate smart agriculture includes

Plate 3.5 Neglected but precious resource for salts in UAE (left) and Bahrain (right) needs attention

proven practical techniques such as mulching, intercropping, conservation agriculture, crop rotation, integrated crop-livestock management, agro-forestry, controlled grazing, and improved water management. It requires innovative practices such as better weather forecasting, early warning systems and risk insurance. It is also very much about getting existing technologies off the shelf and into the hands of farmers, as well as developing new technologies such as drought or flood tolerant crops to meet the demands of the changing climate. Finally, climate smart agriculture is about creating and enabling the policy and environment which will allow for adaptation (World Bank 2011).

14 Commercial Exploitation of Mineral Resources from Highly Saline Areas – The Neglected Resource

The lands of immediate vicinity to the coast are highly vulnerable to sea water intrusion. These soils, overtime, are converted to ***sabkha*** (salt scald) – areas which are not conducive for agricultural activities. Such highly saline lands may, however, be exploited for other uses, such as commercial salt harvesting. This precious resource (Plate 3.5) is neglected for the time being, but has high potential to generate capital.

In Australia, while addressing dryland salinity issues, an approach entitled '***Options for the productive use of salinity – OPUS***' has been successfully used in a National Dryland Salinity Program (PPK E & I Pty Ltd. 2001). One of the options is the industrial use of harvested salts.

The OPUS approach has the following objectives.

- Collate and assess information on innovative options for the productive use of saline land and water, both within Australia and internationally
- Provide guidance and considerations for industry (or industrial) implementation

- Assess the economic and marketing barriers to investment in industries involved in salinity issues
- Suggest the skills, resources and institutional arrangements that would improve our capacity to utilize saline resources and identify areas requiring further research and development.

The OPUS assessed 13 industries, including sheep grazing on saltbush '*Atriplex*' pastures, saline forestry, aquaculture of fish, algal production and desalination.

In this section, however, our emphasis is mainly on salt harvesting and exploitation of the salt(s) for commercial purposes. Sea water is dominant in Na^+ and Cl^- ions relative to other ions (Ca^{2+}, Mg^{2+}, $SO_4{}^{2-}$, $CO_3{}^{2-}$, $HCO_3{}^-$, etc.). Thus, practically speaking, when we talk of salt, it means sodium chloride (NaCl), the mineral name being 'halite'. The PPK E & I Pty Ltd. (2000) described three types of salts which are harvested in different ways. There are three broad categories:

Rock salt – subsurface deposits within the earth, formed millions of years ago, an era when the oceans that covered the planet evaporated and receded, leaving behind salt deposits. Rock salt is mined in the mineral form.

Solar salt – saline sea water is pumped into condensing ponds and then to the saturating ponds. The evaporation leads to salt crystallization, which is harvested. In the United Arab Emirates, sea water intrusion into the coastal areas and subsequent evaporation has developed huge quantities of salts which have the potential for commercial harvesting.

Evaporated salt – here, wells are drilled into underground salt deposits and water is pumped into the wells to dissolve the salts. The resulting brine is pumped to the surface, evaporated and harvested.

There are many uses of salts in the industry. Chemical industry accounts for 55% of global salts consumption. Three main products are:

(i) Caustic soda – NaCl (halite) + H_2O (water) → NaOH (Caustic soda) + HCl (Hydrochloric acid)
(ii) Soda ash, and (iii) Chlorine

There are a number of commercial uses of the above products in the pulp, paper, organic and inorganic chemicals, glass, petroleum, plastics (PCV) and textiles industries (IMC Global 1999; Olsson Industries 2001; Dampier Salt Pty Ltd. 2001; Cheetham Salt Pty Ltd. 2001).

Salts are used globally in the food industry, i.e. preserving and preparing canned and bottled foods, in cheese production, in bakeries and cooking foods, etc.

In Europe or other countries where heavy snow falls are frequent, salt is used to de-ice the roads to facilitate transport. Such a use accounts for 30% of the total salt use in Europe (European Salt Producers' Association 2000).

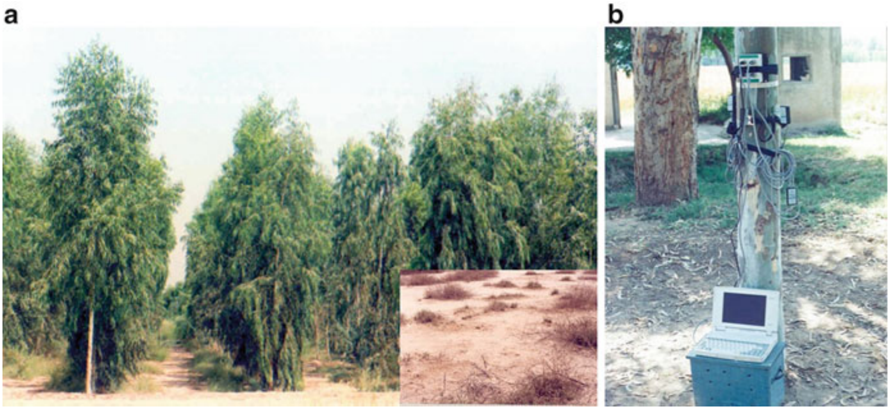

Plate 3.6 (**a**) *Eucalyptus camaldulensis* stand on a saline-sodic soil at the Biosaline Research Station of NIAB (Pakka Anna), near Faisalabad, monitored for tree water use with HeatPulse Data Loggers. (Adapted from Mahmood et al. 2004), (**b**) Setup for monitoring tree water use with HeatPulse Technique

15 Salinity Control Strategy

A salinity control strategy should be to stop the spread of salt-affected soils, with a major objective to greatly reduce the future effects of salinity. This requires a commitment by governments. This strategy/objective can be achieved in a number of ways, including:

- By re-vegetating the shallow water-table areas with deep-rooted trees, and
- Lowering the water-table by pumping, and flushing the salts from soils

Perennial plants and forages, especially alfalfa, are useful for lowering water-table, because they have a longer growing season and take up more water from a greater depth in the soil than annual plants. *Eucalyptus* has been used to lower water-table (***biodrainage)*** as it transpires large volumes of water. Mahmood et al. (2001) reported on the water use of *Eucalyptus* and other salt tolerant tree species, determined by using HeatPulse Data Loggers, under variable field conditions in Punjab province, Pakistan (Plate 3.6).

Eucalyptus camaldulensis on an irrigated, non-saline site near Lahore showed an annual water use of 1393 mm (Table 3.4). Irrigated *Eucalyptus microtheca* at this site and un-irrigated *E. camaldulensis* dependent on saline groundwater on saline soil at Pakka Anna near Faisalabad also transpired over 1000 mm of water per year. *Acacia ampliceps* showed much lesser water use than *E. camaldulensis* in spite of a similar basal area growth at Pakka Anna, whereas lowest annual water use of 235 mm was shown by an under-stocked stand of *Prosopis juliflora* at this site. These results provide an example regarding the range of choice of suitable tree species for site-specific conditions with reference to water availability and objectives of re-vegetation projects.

Table 3.4 Calculated daily and annual water use by plantations on saline sites near Lahore and Pakka Anna near Faisalabad, Pakistan. (Adapted from Mahmood et al. 2001)

Plot details	Soil $EC_{1:1}$ (dS/m)	Days monitored	Mean daily water use (mm) ± S.E.	Annual water use (mm)
Lahore				
Eucalyptus camaldulensis	2.5–5.0	333	3.82 ± 0.07	1393
E. microtheca	2.5–5.0	322	2.87 ± 0.06	1084
Pakka Anna near Faisalabad				
E. camaldulensis (low salinity)	3.2–4.0	330	3.20 ± 0.07	1169
E. camaldulensis (high salinity)	6.2–8.5	285	2.99 ± 0.09	1090
Acacia ampliceps	5.0–5.2	317	1.71 ± 0.05	624
Prosopis juliflora	6.1–7.0	262	0.64 ± 0.01	235

The strategy should direct the farming community's efforts to areas where salinity is, or will be, a major problem. The main emphasis should be to provide further encouragement, assistance and technical support to research scientists in order to identify the areas where the most effort should be directed. These areas, once identified, should be considered as '***hot spots***' and most of the resources should be directed into rectifying and preventing future enlargement of these hot spots.

Working together to tackle the salinity problems is sensible, especially when the cause may not necessarily be confined to one property. Governments should take appropriate steps in improving long-term productivity and amenity value of saline areas. Grants and incentives should be made available to educate the farming community, to make it aware of the land degradation problem and the need for farmers to move quickly and properly in order to protect their livelihood.

Education of the farming community is vital in increasing the community's awareness and understanding of salinity, so that the above strategy is widely supported and acted upon. Advisory programs should be developed using extension workers so that farmers can plan and use salinity control practices on their farms.

Salinity mapping on a whole farm scale is the best practice for crop selection. Salinity exhibitions for community education should be arranged in government institutes, and demonstration days at the farmers' fields are also useful. Preparation of introductory brochures for salinity control and management at the farm level and their distribution to the farming community can enhance the understanding of how to best tackle salinity in a sustainable way. The awareness of the problem by local school teachers can give students a hands-on experience and help them discuss options with their students. After all, today's students will be tomorrow's land managers.

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