CHAPTER FOUR

Phytoremediation of Sodic and Saline-Sodic Soils

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Sodicity-induced soil degradation is a major environmental constraint with severe negative impacts on agricultural productivity and sustainability in arid and semiarid regions. As an important category of salt-affected soils, sodic soils are characterized by excess levels of sodium ions (Na^+) in the soil solution phase as well as on the cation exchange complex, exhibiting unique structural problems as a result of certain physical processes (slaking, swelling, and dispersion of clay) and specific conditions (surface crusting and hardsetting). Saline-sodic soils, another category of salt-affected soils, are generally grouped with sodic soils because of several common properties and management approaches. Sodic and saline-sodic soils occur within the boundaries of at least 75 countries, and their extent has increased steadily in several major irrigation schemes throughout the world. The use of these soils for crop production is on the increase as they are a valuable resource that cannot be

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neglected, especially in areas where significant investments have already been made in irrigation infrastructure. It is imperative to find ways to improve sodic and saline-sodic soils to ensure that they are able to support highly productive land-use systems to meet the challenges of global food security.

Nearly a century-old record reveals amelioration of sodic soils through the provision of a readily available source of calcium (Ca^{2+}) to replace excess Na^+ on the cation exchange complex; the displaced Na^+ subject to leaching from the root zone through the application of excess irrigation water in the presence of a drainage system. Many sodic soils do contain inherent or precipitated sources of Ca^{2+}, that is calcite ($CaCO_3$), at varying depths within the soil profile. However, due to its negligible solubility, natural dissolution of calcite does not provide sufficient quantities of Ca^{2+} to affect soil amelioration with routine management practices. Consequently, amelioration of these soils has been predominantly achieved through the application of chemical amendments. However, amendment costs have increased prohibitively over the past two decades due to competing demands from industry and reductions in government subsidies for their agricultural use in several developing countries. In parallel, scientific research and farmers' feedback have demonstrated that sodic soils can be brought back to a highly productive state through a plant-assisted approach generically termed "phytoremediation." Typical plant-based strategies for contaminated soils, such as those containing elevated levels of metals and metalloids, work through the cultivation of specific plant species capable of hyperaccumulating target ionic species in their shoots, thereby removing them from the soil. In contrast, phytoremediation of sodic soils is achieved by the ability of plant roots to increase the dissolution rate of calcite, thereby resulting in enhanced levels of Ca^{2+} in soil solution to effectively replace Na^+ from the cation exchange complex. Phytoremediation has shown to be advantageous in several aspects: (1) no financial outlay to purchase chemical amendments, (2) accrued financial or other benefits from crops grown during amelioration, (3) promotion of soil-aggregate stability and creation of macropores that improve soil hydraulic properties and root proliferation, (4) greater plant-nutrient availability in soil after phytoremediation, (5) more uniform and greater zone of amelioration in terms of soil depth, and (6) environmental considerations in terms of carbon sequestration in the postamelioration soil. Phytoremediation is particularly effective when used on moderately saline-sodic and sodic soils. It is a viable solution for resource-poor farmers through community-based management, which would help in strengthening the linkages among researchers, farm advisors, and farmers. These linkages will continue to be fostered as the use of sodic soils becomes more prevalent. The success of phytoremediation of sodic soils requires a greater understanding of the processes fostering phytoremediation, the potential of plant species to withstand ambient salinity and sodicity levels in soil and water, and also of the uses and markets for the agricultural products produced. Strategic research on such aspects would further elucidate the role of phytoremediation in the restoration of sodic soils for sustainable agriculture and conservation of environmental quality.

1. Introduction

Soil degradation resulting from salinity and/or sodicity is a major environmental constraint with severe negative impacts on agricultural productivity and sustainability, particularly in arid and semiarid regions of the world (Pitman and Laüchli, 2002; Qadir *et al*., 2006; Suarez, 2001; Tanji, 1990). Salt-affected soils are characterized by excess levels of soluble salts (salinity) and/or Na^+ in the solution phase as well as on cation exchange complex (sodicity). These salts and Na^+ originate either by the weathering of parent minerals (causing primary salinity/sodicity) or from anthropogenic activities, involving the inappropriate management of land and water resources (contributing to secondary salinity/sodicity).

Salt-affected soils occur within the boundaries of at least 75 countries (Szabolcs, 1994). These soils also occupy more than 20% of the global irrigated area (Ghassemi *et al*., 1995); in some countries, they occur on more than half of the irrigated land (Cheraghi, 2004). Over the last few decades, salt-prone soil degradation has increased steadily in several major irrigation schemes throughout the world. Examples include Indo-Gangetic Basin in India (Gupta and Abrol, 2000), Indus Basin in Pakistan (Aslam and Prathapar, 2006), Yellow River Basin in China (Chengrui and Dregne, 2001), Euphrates Basin in Syria and Iraq (Sarraf, 2004), Murray-Darling Basin in Australia (Herczeg *et al*., 2001; Rengasamy, 2006), and San Joaquin Valley in the United States (Oster and Wichelns, 2003). Salt- and irrigation-induced soil degradation is prevalent in the Aral Sea Basin of Central Asia with the consequent environmental changes in that region being considered as the largest ones caused by humanity (Cai *et al*., 2003). Several other examples of salt-prone soil degradation exist elsewhere in the world (Ghassemi *et al*., 1995; Szabolcs, 1994).

Salt-prone soil degradation has triggered imbalances between the functions (goods and services) supplied by the natural resources (land and water) and the demands of societies that exploit these functions. Since such degradation occurs both "on-site" and "off-site," it affects the livelihoods within and outside the farming communities (Abdel-Dayem, 2005). In comparison with the biophysical aspects, the social and economic dimensions of salt-induced soil degradation have received little attention. It is generally recognized that a large proportion of these soils occur on land inhabited by smallholder farmers, who rely on this resource to satisfy their food and feed needs (Qadir *et al*., 2006). Although it is easy to link salinity and sodicity to poverty, limited information is available that puts a monetary value on their social and economic impacts (Ali *et al*., 2001). The information available addresses mainly crop-yield losses on salt-affected soils, revealing estimates of annual global income losses in excess of US$12 billion (Ghassemi *et al*., 1995).

As an important category of salt-affected soils, sodic soils exhibit unique structural problems as a result of certain physical processes (slaking, swelling, and dispersion of clay) and specific conditions (surface crusting and hard-setting) (Qadir and Schubert, 2002; Shainberg and Letey, 1984; Sumner, 1993). These problems can affect water and air movement, plant-available water-holding capacity, root penetration, seedling emergence, runoff and erosion, as well as tillage and sowing operations (Oster and Jayawardane, 1998). In addition, changes in the proportions of soil solution and exchangeable ions lead to osmotic and ion-specific effects together with imbalances in plant nutrition, which may range from deficiencies of several nutrients to high levels of Na^+ (Grattan and Grieve, 1999; Mengel and Kirkby, 2001; Naidu and Rengasamy, 1993). Such physical and chemical changes have a bearing on the activity of plant roots as well as on soil microbes, and ultimately on crop growth and yield. Saline-sodic soils, another category of salt-affected soils, are generally grouped with sodic soils because (1) they share several characteristics and (2) the management approaches required for either soil type are similar. Sodic and saline-sodic soils account for more than 50% of the world's salt-affected area (Beltrán and Manzur, 2005; Tanji, 1990).

Despite considerable research undertaken in elucidating the cause and effects of salinity and sodicity on the chemical and physical properties of sodic and saline-sodic soils, there has been a paucity of examples that have successfully translated this understanding into effective amelioration and sustainable management (Oster *et al.*, 1999). The use of sodic and saline-sodic soils for crop production is expected to increase in the near future, which could aggravate salinity and sodicity problems through mismanagement. Despite the implications associated with the amelioration and management of sodic and saline-sodic soils, the fact remains that these soils are a valuable resource that cannot be neglected, especially in areas where significant investments have already been made in irrigation infrastructure (Qadir *et al.*, 2006). Consequently, if the challenges of global food security are to be met, it is imperative to find ways to improve these soils to ensure that they are able to support highly productive land-use systems.

Over the past 100 years, several different approaches—involving chemical amendments, tillage operations, crop-assisted interventions, water-related approaches, and electrical currents—have been used to ameliorate sodic and saline-sodic soils. Of these, chemical amendments have been used most extensively (Oster *et al.*, 1999). A number of tillage options, such as deep plowing and subsoiling, have also been used to break up the shallow, dense, sodic clay pans and/or natric horizons that occur within 0.4 m of the soil's surface (Abdelgawad *et al.*, 2004; Rasmussen *et al.*, 1972). However, in recent decades, the crop-based approach, phytoremediation, has shown promise as an effective low-cost amelioration intervention (Ghaly, 2002; Ilyas *et al.*, 1993; Robbins, 1986a), as it is much cheaper than chemical amelioration, the costs of which are prohibitively high for resource-poor farmers in many developing countries (Qadir and Oster, 2004).

This chapter focuses on the phytoremediation of sodic and saline-sodic soils. After providing information on the characterization of sodic and saline-sodic soils and the degradation processes that occur resulting in their formation, we address the process of phytoremediation of these soils along with different aspects such as historical perspective, driving forces contributing to the process, comparison of phytoremediation with other amelioration approaches, selection of phytoremediation crops, and the role of cropping in securing environmental integrity under sodic and saline-sodic conditions. Finally, we offer our views on the prospects for improved management of sodic and saline-sodic soils as an opportunity to shift from subsistence farming to progressive and income-generating ventures.

2. Description of Sodic and Saline-Sodic Soils

Sodic and saline-sodic soils are generally described in terms of the relative amounts of Na^+ in the soil solution or on the cation exchange complex, given the accompanying levels of salinity. Therefore, soil sodicity represents the combined effects of (1) salinity as measured by electrical conductivity of the soil, and (2) soluble Na^+ concentration relative to soluble divalent cation concentration in soil solution, that is sodium adsorption ratio (SAR), or as exchangeable sodium fraction (ESF) expressed as a percentage, that is exchangeable sodium percentage (ESP). SAR is calculated by using Eq. (1):

$$\text{SAR} = \frac{C_{\text{Na}}}{[(C_{\text{Ca}} + C_{\text{Mg}})/2]^{1/2}} \tag{1}$$

where C represents concentrations in soil solution in terms of mmol$_c$ liter^{-1} (mmol$_c$ liter^{-1} = meq liter^{-1}) of the cations identified as subscripts. ESP is calculated from Eq. (2) by incorporating the values of exchangeable Na^+ (E_{Na}) and cation exchange capacity (CEC), both expressed as mmol$_c$ kg^{-1} or cmol$_c$ kg^{-1} (cmol$_c$ kg^{-1} = meq 100 g^{-1}) of the soil

$$\text{ESP} = \frac{100(E_{\text{Na}})}{\text{CEC}} \tag{2}$$

ESP may also be calculated by replacing CEC in Eq. (2) with the sum of exchangeable cations such as calcium (E_{Ca}), magnesium (E_{Mg}), potassium (E_{K}), exchangeable sodium (E_{Na}), and aluminum (E_{Al}), with all the cations expressed as mmol$_c$ kg^{-1} or cmol$_c$ kg^{-1} of the soil (Sumner *et al.*, 1998)

$$\text{ESP} = \frac{100(E_{\text{Na}})}{(E_{\text{Ca}} + E_{\text{Mg}} + E_{\text{K}} + E_{\text{Na}} + E_{\text{Al}})} \tag{3}$$

The sum of exchangeable cations, as given in Eq. (3), may be replaced by the term effective cation exchange capacity (ECEC). The incorporation of E_{Al} in Eq. (3) is for acid sodic soils (pH < 6), which may contain some Al^{3+} on the cation exchange complex. However, most sodic soils are alkaline in reaction with pH more than 7.

Various approximate relationships have been derived between ESP and SAR of soils belonging to different areas of the world. Based on the ESP and SAR values of soil samples from the Western states, the following relationship [Eq. (4)] was developed by the US Salinity Laboratory Staff (1954):

$$\text{ESP} = \frac{\{100[-a + b(\text{SAR})]\}}{\{1 + [-a + b(\text{SAR})]\}} \tag{4}$$

where $a = 0.0126$ and $b = 0.01475$. The relationships between ESP and SAR have also been developed for soils from other regions and countries (Franklin and Schmehl, 1973; Ghafoor *et al.*, 1988; Paliwal and Gandhi, 1976; Table 1). It is largely accepted that ESP and SAR values remain close to each other within the range 0–40, which is most common in agricultural soils. Therefore, SAR has been widely used as an approximation of ESP within this range.

An ESP of 15 (SAR $\sim$ 13) is generally taken to be the threshold below which soils are classified as nonsodic, and above which soils are dispersive and suffer serious physical problems when water is applied. However, considerable data exist for infiltration rates and hydraulic conductivities that show that soil behavior typical of sodic soils may occur at ESP values of less than 15 if accompanying levels of salinity (EC_e) are lower than 4 dS m^{-1} (Sumner *et al.*, 1998). Therefore, the principal factor determining the extent of the adverse effects of Na^+ on soil properties is the ambient electrolyte concentration in the soil solution, with low concentrations exacerbating the deleterious effects of exchangeable Na^+.

Other nomenclature—alkali, black alkali, solonetz, and slick-spot—has also been used for sodic and saline-sodic soils in different parts of the world. For instance, alkali soils are characterized by high sodicity (ESP > 15) and pH (pH > 8.3), and contain soluble carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions of Na^+. The concentrations of Na^+ are greater than the accompanying levels of chloride (Cl^-) and sulfate (SO_4^{2-}), that is $C_{\text{Na}} : (C_{\text{Cl}} + C_{\text{SO}_4})$ ratio greater than 1. Alternatively, the ratio $(2C_{\text{CO}_3^{2-}} + C_{\text{HCO}_3^-}) : (C_{\text{Cl}} + 2C_{\text{SO}_4})$ is more than 1 in soil solution phase, when expressed as mol m^{-3} (Chhabra, 2005). These soils contain Na^+ and $CO_3^{2-} + HCO_3^-$ as the dominant ions and tend to have low salinities and high pH values, which cause an increase in

Table 1 Approximate relationships derived between ESP and SAR of soils from different regions of the globe

Equations	Samples[a]	ESP at SAR 20[b]	References
ESP = [100 (−0.0126 + 0.01475 SAR)]/[1 + (−0.0126 + 0.01475 SAR)]	59	22	US Salinity Laboratory (1954)
ESP = [100 (0.0063 + 0.0124 SAR)]/[1 + (0.0063 + 0.0124 SAR)]	15	20	Franklin and Schmehl (1973)
ESP = [100 (0.1149 + 0.0109 SAR)]/[1 + (0.1149 + 0.0109 SAR)]	150	25	Paliwal and Gandhi (1976)
ESP = [100 (−0.0867 + 0.02018 SAR)]/[1 + (−0.0867 + 0.02018 SAR)]	180	24	Ghafoor *et al.* (1988)
ESP = [100 (−0.0268 + 0.02588 SAR)]/[1 + (−0.0268 + 0.02588 SAR)]	144	33	Ghafoor *et al.* (1988)

[a] Number of soil samples used to develop the relationship between ESP and SAR.
[b] Equivalent values of ESP calculated at SAR levels of 20.

swelling and dispersion of clay (Gupta *et al.*, 1984). On the other hand, the pH of sodic soils can be greater or less than 7 and such soils can be either saline or nonsaline.

3. Degradation Processes in Sodic and Saline-Sodic Soils

Sodicity influences the soil at the level of the clay fraction (Quirk, 2001), which is categorized with a particle size of <2-μm diameter. It is an important component of the soil matrix because of its charge properties and larger surface area per unit mass than other major fractions such as silt and sand. In an aqueous suspension, the charge on clay particles is neutralized by hydrated ions of opposite charge. In the case of sodic and saline-sodic soils, clay surfaces usually carry a net negative charge, which is neutralized by a diffuse cloud of ions in which the concentrations of cations increase and that of anions decrease as the surface is approached. This phenomenon is commonly referred to as a diffuse double layer. This electrical layer consists of the surface charge and compensating counterions that form a surrounding ion swarm.

The thickness of the diffuse double layer depends on the nature of exchangeable cations and electrolyte concentration of soil solution (Van Olphen, 1977; Verwey and Overbeek, 1948). The counterions are subject to two opposing tendencies: (1) the cations are attracted electrostatically to the negatively charged clay surface; and (2) the cations tend to diffuse away from the surface of clay particles where their concentration is higher, into the bulk solution where their concentration is low. Such opposing tendencies result in an exponentially decreasing exchangeable cation concentration with distance from the negatively charged clay surface. Since divalent cations are retained by the clay surface with a force greater than the monovalent cations, the thickness of the diffuse double layer is more compressed when divalent cations dominate the system. In a similar way, increasing the electrolyte concentration in the bulk solution has a compressing effect on the double layer since high concentrations reduce the tendency of exchangeable cations to diffuse away from clay surface (Van Olphen, 1977).

When two clay colloids approach each other, their diffuse double layers overlap and the electrical repulsion forces are activated between the two positively charged exchangeable ion atmospheres. Such electric repulsion force is also known as "swelling pressure." The greater the compression of the exchangeable cations toward the clay surface the smaller the repulsion forces between the clay colloids, that is the smaller the swelling pressure, resulting in a lower propensity for clay swelling. Clay swelling is a process that reduces the radius of soil pores and plays a crucial role in reducing hydraulic conductivity of the soil (Quirk and Schofield, 1955; Rengasamy *et al.*, 1984; Russo and Bresler, 1977; Xiao *et al.*, 1992), thereby influencing the movement of water through the soil profile. The process decreases with increasing (1) electrolyte concentration of the bulk solution, and (2) valence of the exchangeable cations, as in the case of polyvalent cations. For example, montmorillonite clay dominated by Na^+ swells freely in low electrolyte solutions as the single platelets tend to persist in such dilute salt solutions. However, when divalent cations such as Ca^{2+} dominate the montmorillonite surfaces, individual clay platelets develop aggregates, which are known as tactoids (Blackmore and Miller, 1961). Synonymous terms for tactoids are quasicrystals (Quirk and Aylmore, 1971) or clay domains (Sumner, 1993). Tactoids consist of 4–9 clay platelets in parallel array with interplatelet distance of 0.9 nm (Shainberg and Letey, 1984; Sposito, 1984). The Ca^{2+}-dominated clay fraction behaves like a system having a much smaller surface area. Thus, swelling of Ca^{2+}-montmorillonite remains much smaller than that of Na^+-montmorillonite because only the external surfaces of the quasicrystals contribute to swelling.

Soil degradation under sodic conditions occurs through a series of mechanisms (Fig. 1). Initially, the dry soil aggregates are strong with high attractive forces between clay particles, but application of water results in wetness of soil aggregates and hydration reactions lead to repulsive forces between clay particles, which reduce the attraction between them resulting in weak wet aggregates (Rengasamy and Sumner, 1998). Generally, initial hydration of sodic clays leads to slaking and swelling. Slaking refers to the breakdown of macroaggregates into microaggregates on wetting (Abu-Sharar *et al*., 1987; Cass and Sumner, 1982). This process results in a reduction in number and size of large pores at the soil surface, thereby limiting infiltration of rainfall or irrigation water (Nelson and Oades, 1998). Dispersion is a process that leads to the release of individual clay platelets from soil aggregates. When individual clay particles are detached from soil aggregates, dispersion begins and creates an unstable structure. In case of extensive hydration of sodic and saline-sodic soils, the release and spontaneous dispersion of clay particles from the aggregates occurs. Flocculation of such clay particles may be brought about by the addition of electrolytes, particularly Ca^{2+}, which results in osmotic effects, causing dehydration of the clay–water system, and reduces the distance of separation between particles (Rengasamy and Sumner, 1998).

Soil aggregates at the surface have a greater degree of vulnerability to the degradation processes because of the stresses generated by rapid water uptake, release of entrapped air, mechanical impact and stirring action caused by the flowing water applied through irrigation or precipitation (Oster and Jayawardane, 1998). In addition, the surface soil is more unstable

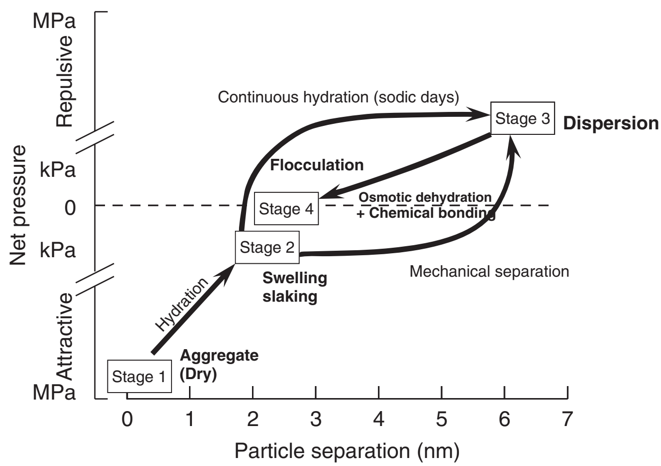

Figure 1 Schematic presentation of processes and intensity of attractive and repulsive forces involved when a dry aggregate of a sodic soil is wetted [adapted from Rengasamy and Sumner (1998)].

than the underlying soil because of a low electrolyte concentration (Shainberg *et al.*, 1992) and high E_{Na} (Shainberg and Letey, 1984) and E_{Mg} levels (Keren, 1991). Therefore, aggregates at the soil surface are destroyed first through the processes of slaking and dispersion. As a consequence a rearrangement of soil particles occurs on the surface on drying, resulting in a densely packed thin soil layer with high shear strength, which is referred to as a structural crust or seal (McIntyre, 1958; Moore and Singer, 1990). Crust formation in soils is attributed to two processes: (1) physical disintegration of soil aggregates and their compaction, and (2) dispersion and movement of clay particles into a region of 0.1- to 0.5-mm depth, where they lodge and clog the conducting pores (Agassi *et al.*, 1981; McIntyre, 1958). Although both processes occur simultaneously, physical disintegration of soil aggregates enhances dispersion and movement of clay particles. In addition, physical disintegration of soil aggregates is controlled mainly by the type of cations and their concentrations in the soil and applied water (Agassi *et al.*, 1981; Kazman *et al.*, 1983). Crusting is a major mechanism affecting the steady-state infiltration rate in soils of arid and semiarid regions where organic matter is usually low and soil structure is unstable.

With effects similar to sealing, hardsetting is another mechanism leading to soil degradation under sodic conditions. The major difference between hardsetting and sealing is that sealing effects remain within 0.1- to 0.5-mm depth of the soil, while hardsetting leads to complete aggregate breakdown and clay movement usually within the entire plowing zone. On drying, hardsetting exhibits massive, compact, and hard conditions in the upper soil layer (Mullins *et al.*, 1990), which is not disturbed or indented by the pressure of a forefinger. Occurrence of hardsetting in soils reduces infiltration rate and increases runoff and erosion and impairs water movement into and through the soil and decreases seedling emergence with subsequent impacts on crop growth and yield.

4. Phytoremediation of Sodic and Saline-Sodic Soils

Sodic and saline-sodic soils are ameliorated by the provision of a readily available source of Ca^{2+} to replace excess Na^+ on the cation exchange complex. The displaced Na^+ is leached from the root zone through the application of excess irrigation water. This requires adequate amounts of water and unimpeded flow through the soil profile as well as the provision of natural or artificial drainage systems (Gupta and Abrol, 1990; Oster *et al.*, 1999; Rhoades and Loveday, 1990), which plays an important role in the management of drainage water in a sustainable manner.

Considering the fact that sodic soil amelioration is accomplished by providing a source of Ca^{2+}, most sodic and saline-sodic soils do contain a source of Ca^{2+}, that is calcite ($CaCO_3$), at varying depths within the soil profile. Calcite may be a constituent of the parent material or formed *in situ* through precipitation as coatings on soil particles and in pores that may result in cementation of particles. However, due to its negligible solubility (0.14 mmol liter^{-1}), natural dissolution of calcite does not provide sufficient quantities of Ca^{2+} to affect soil amelioration at partial pressures of carbon dioxide (P_{CO_2}) that are typically present in the atmosphere. A further common Ca^{2+}-containing mineral in sodic and saline-sodic soils is dolomite. The solubility of dolomite is several-fold less than calcite. The more soluble $CaCO_3$ minerals such as vaterite, aragonite, or $CaCO_3$ hydrates are not commonly found in soils or observed to form pedogenically (Suarez and Rhoades, 1982). Consequently, amelioration of these soils has been predominantly achieved through the application of chemical amendments (Gupta and Abrol, 1990; Oster *et al.*, 1999; Rhoades and Loveday, 1990). In this respect, amendments such as gypsum ($CaSO_4 \cdot 2H_2O$) supply soluble sources of Ca^{2+} to the soil solution, which then replace excess Na^+ on the exchange complex. Other amendments such as sulfuric acid (H_2SO_4) assist in increasing the dissolution rate of calcite to release adequate amounts of Ca^{2+} in soil solution (Table 2). A century-old practice in sodic soil management reveals extensive use of chemical amendments, particularly gypsum, in different parts of the world.

There have been some constraints with chemical amelioration of sodic soils in several developing countries because of (1) low quality of amendments containing a large fraction of impurities; (2) restricted availability of amendments when actually needed by the farmers for amelioration; and/or (3) increased costs due to competing demands for amendments in the

Table 2 Chemical composition and equivalent amount of a chemical amendment that can substitute One metric ton (t) of gypsum in ameliorating sodic soils[a]

Amendment	Chemical composition	Amount equivalent to 1 Mg of gypsum
Gypsum	$CaSO_4 \cdot 2H_2O$	1.00
Calcium chloride	$CaCl_2 \cdot 2H_2O$	0.85
Calcium carbonate	$CaCO_3$	0.58
Sulfuric acid	H_2SO_4	0.57
Ferrous sulfate	$FeSO_4 \cdot 7H_2O$	1.61
Ferric sulfate	$Fe_2(SO_4)_3 \cdot 9H_2O$	1.09
Aluminum sulfate	$Al_2(SO_4)_3 \cdot 18H_2O$	1.29

[a] The amount of any amendment to be applied for sodic soils amelioration is based on the amount equivalent to that of gypsum, which is called GR and determines the amount of calcium (Ca^{2+}) needed to replace sodium (Na^+) from the soil.

industrial sector and substantial reductions in or termination of government subsidies for agricultural use of the amendments. With the last factor having overriding importance, chemical amelioration has become prohibitively expensive for subsistence farmers since the early 1980s. In parallel, scientific research and farmers' feedback have demonstrated that sodic and saline-sodic soils can be ameliorated through a plant-assisted approach, phytoremediation (Kumar and Abrol, 1984; Mishra *et al.*, 2002; Qadir *et al.*, 2002; Robbins, 1986a).

Typical plant-based amelioration strategies for contaminated soils, such as those containing elevated levels of metals and metalloids, work through the cultivation of specific plant species capable of hyperaccumulating target ionic species in their shoots, thereby removing them from the soil (Baker *et al.*, 1994; McGrath *et al.*, 2002; Salt *et al.*, 1998). In contrast, phytoremediation of sodic and saline-sodic soils is achieved by the ability of plant roots to increase the dissolution rate of calcite, thereby resulting in enhanced levels of Ca^{2+} in soil solution to effectively replace Na^{+} on the cation exchange complex. The salinity levels in soil solution during phytoremediation maintain adequate soil structure and aggregate stability that facilitate water movement through the soil profile and enhance the amelioration process (Oster *et al.*, 1999). Synonymous terminology for phytoremediation includes vegetative bioremediation, phytomelioration, and biological reclamation.

4.1. Historical perspective

In the 1920s and 1930s, Kelley and associates (Kelley, 1937; Kelley and Brown, 1934) conducted a seminal series of field experiments in California, which are among the earliest research studies on phytoremediation of sodic soils (Qadir and Oster, 2002). The soil used in these studies was a fine sandy loam solonetz (sodic) located on the Kearney Ranch near Fresno. It had the following chemical properties in the upper 0.3 m layer: pH = 9.2–9.7; CEC = 43–44 $mmol_c\ kg^{-1}$; ESP = 57–70. Based on the reported cation composition, the salinity levels ($EC_{1:5}$) were 6.1–7.2 dS m^{-1}. The soil was approximately uniform in texture to a depth of 0.6–0.9 m, below which there was a compact layer that was 0.05- to 0.15-m thick and rich in calcite.

In the first phase of the field studies, Kelley and Brown (1934) applied a total of 37 Mg ha^{-1} of gypsum in two splits, 22 Mg in 1920 and 15 Mg in 1921. Each year after gypsum application the plots were flooded and kept submerged for 3 weeks by repeated applications of well water (EC = 0.3 dS m^{-1}, SAR = 0.7). The same amount of water was applied to the phytoremediation treatment, which consisted of cropping and irrigation without gypsum application. Barley (*Hordeum vulgare* L.) was the first crop used as phytoremediation treatment, which was grown for 2 years. It was followed by a 1-year green manuring each by Indian sweet clover (*Melilotus indicus* L.) and white sweet clover (*M. albus* Medik.), and 5 years under continuous alfalfa (*Medicago sativa* L.). After the final alfalfa crop, the plots were kept fallow for 1 year and then cropped with cotton (*Gossypium hirsutum* L.), the first postamelioration crop. Cotton yields were 1.82 Mg ha^{-1} for the gypsum treatment and 2.10 Mg ha^{-1} for the phytoremediation treatment. ESP of the upper 0.3 m soil depth decreased from 70 to 5 in the gypsum-treated soil and from 65 to 6 in the plots subjected to phytoremediation (Table 3).

In the next phase of the field studies in California, Kelley (1937) initiated a phytoremediation experiment in 1930 with Bermuda grass [*Cynodon dactylon* (L.) Pers.] as the first phytoremediation crop used in the sequence. The grass was grown for 2 years followed by cultivation of barley for 1 year, alfalfa for 4 years, and oats (*Avena sativa* L.) for 1 year. In all, there was 8 years of cropping. In the postamelioration soil, the ESP of the upper 0.3 m soil depth decreased from 57 to 1 (Table 3), with a reduction in average profile (0–1.2 m) ESP from 73 to 6. The overall decrease in ESP under the phytoremediation treatment was even greater than that obtained with the gypsum treatment of the earlier experiment, possibly owing to the introduction of Bermuda grass at the beginning of the cropping sequence. In addition, there was more uniform and greater zone of amelioration in terms of soil depth.

The phytoremediation approach used by Kelley and coworkers in California (Kelley, 1937; Kelley and Brown, 1934) was based on the same principles and involved some of the techniques used in the irrigated-meadow experiment at Bekescsaba, Hungary (deSigmond, 1924). In the Hungarian experiment, a mixture of several different grasses and legumes was grown successfully on a heavy (low-permeability) black-alkali (sodic) soil, which

Table 3 Effect of chemical (gypsum) and phytoremediation (cropping) treatments on exchangeable sodium percentage (ESP) of the Fresno soil (based on the data reported by Kelley and Brown (1934) and Kelley (1937)

	1920–1930				1930–1937	
	Gypsum[a] + Cropping[b]		Cropping[c]		Cropping[c]	
Soil depth (m)	Initial	Final	Initial	Final	Initial	Final
			ESP (%)			
0.0–0.3	70	5	65	6	57	1
0.3–0.6	67	8	70	21	97	4
0.6–0.9	54	9	46	26	90	13
0.9–1.2	35	19	28	53	46	4
Profile mean	49	10	52	27	73	6

[a] Gypsum application at 37 Mg ha^{-1} in two splits: 22 Mg in 1920 and 15 Mg in 1921.
[b] Cultivation of barley for 2 years, green manuring by clovers for 2 years, and alfalfa grown for 5 years.
[c] Cultivation of Bermuda grass for 2 years, barley for 1 year, alfalfa for 4 years, and oats for 1 year.

resulted in gradual amelioration of the soil. Similar crop-based approaches leading to the management of sodic soils were successfully used at Fallon, Nevada (Knight, 1935) and at Vale, Oregon (Wursten and Powers, 1934).

The last major effort concerning amelioration of salt-prone soils in California was on new lands along the west side of the San Joaquin Valley brought under irrigation during the 1950s and 1960s. The soils were calcareous, with a wide variation in terms of salinity, sodicity, gypsum, and boron (B) levels. Cropping during amelioration was a common practice in the area with new lands. Chemical amendments were used selectively, with reclamation being possible without them on many soils (Kelley, 1951; Overstreet *et al*., 1955). Gypsum, sulfur, and sulfuric acid were used when an increased rate of amelioration was desired. Barley, a winter crop, was usually the first crop grown on new lands as a part of the amelioration process. In addition to annual rainfall, the amount of water used for irrigation and leaching of salts was supplemented by border irrigation. After one or more barley crops, cotton was often added to the rotation. Cotton fields were ripped before planting, amended with gypsum if desired, listed to create furrows, and preirrigated. Large amounts of water (0.25–0.35 m) were infiltrated during the preirrigation phase, resulting in considerable leaching and subsequent amelioration of the soil.

Various cropping systems have been used in the twentieth century by farmers elsewhere in the world for the management of salt-prone soils. The farming history of the Indian Subcontinent reveals the cultivation of certain salt-resistant grasses and trees as an important step in the management of salt-affected soils. The prominent grass and forage species used for soil amelioration were: Bermuda grass locally known as *dub* grass; Kallar or Karnal grass [*Leptochloa fusca* (L.) Kunth] commonly known as *narri*; fodder cane (*Saccharum spontaneum* L.) locally identified as *kans* grass; and sesbania [*Sesbania bispinosa* (Jacq.) W. Wight] (Singh, 1998). The results of field experiments in the early part of the twentieth century supported by soil analyses found the use of sesbania as an important intervention for fodder, green manuring, and improvement of salt-affected soils (Dhawan *et al*., 1958; Uppal, 1955).

Most farmers in the Indian Subcontinent typically began amelioration during high rainfall (0.6–0.9 m) months of July to September (Gupta and Abrol, 1990; Oster *et al*., 1999). Farmers' financial sources had a pivotal role in using different amelioration options, which included: (1) applying gypsum at rates of about 10–15 Mg ha^{-1}, sometimes based on personal experience without testing the soil for actual requirement of gypsum; (2) leaching with excessive irrigations for about 15–20 days, prior to transplanting rice seedlings; (3) installing tubewells for groundwater pumping in high water table areas, sometimes with a government subsidy, and utilizing the pumped water for irrigation and amelioration purposes; (4) cultivating certain salt-resistant crops without the application of chemical amendments; (5) prolonged leaching and accompanying application of farm manure; and (6) green manuring, usually with sesbania species, prior to rice cultivation. Sesbania green manuring is widely practiced on salt-affected soils in terms of an increase in nutrient availability status and a decrease in salinity and sodicity levels (Gupta and Abrol, 1990; Qadir *et al.*, 2001).

The pioneer work of Kelley and coworkers (Kelley, 1937; Kelley and Brown, 1934) and others (deSigmond, 1924; Knight, 1935; Wursten and Powers, 1934) clearly demonstrated the successful amelioration of calcareous sodic soils accomplished by the selection of appropriate plant species and their cropping sequence. However, these studies were long term as it took nearly 10 years to demonstrate the amelioration effects of the crop-assisted approach. In another experiment (Kelley, 1951), a different combination of cropping was used with similar levels of soil amelioration observed after 7 years. While looking at decreases in soil sodicity levels in the phytoremediation treatment, it is argued that sufficient amelioration had already been achieved even earlier than the 7-year period. This might well have been demonstrated had the soil sampling and respective analyses made on a yearly basis after the initiation of these studies. However, the general perception at that point in time reflected the crop-based approach as an intervention that may take several years to ameliorate calcareous sodic and saline-sodic soils. Understanding of the driving forces leading to the enhancement of the phytoremediation process in terms of temporal and technical efficiencies was rudimentary at that time. Chemical amendments such as gypsum were available and the amendment costs were affordable by the farmers mainly because of the provision of government subsidies in many countries. Although phytoremediation involved even lower levels of initial investment, its pace of soil amelioration as perceived at that time did not attract many scientists, farm advisors, agricultural extension workers, and farmers of salt-affected soils to a great extent.

This scenario did not change much until the early 1980s when the cost of the commonly used chemical amendment, gypsum, increased in several parts of the world because of its increased usage by industry and reduction in government subsidies to farmers for its purchase. This provided an incentive for additional research on alternative and efficient methods of low-cost amelioration of sodic soils. Promising results obtained by Robbins (1986a,b) on the amelioration of a calcareous sodic soil as a result of cropping and irrigation without gypsum application stimulated research into phytoremediation. Field-scale studies in the Indian Subcontinent around the same time (Ahmad *et al.*, 1990; Kumar and Abrol, 1984; Singh and Singh, 1989) demonstrated that amelioration through phytoremediation was achievable in much less time than initially anticipated. Such findings were based on the use of appropriate plant species and irrigation and soil management practices that assisted in higher rates of soil amelioration (Qadir and Oster, 2002).

4.2. Mechanisms and processes driving phytoremediation

Phytoremediation of calcareous sodic and saline-sodic soils ($Phyto_{\text{Sodic}}$) assists in enhancing the dissolution rate of calcite through processes at the soil–root interface resulting in increased levels of Ca^{2+} in soil solution. It is a function of the following factors:

$$Phyto_{\text{Sodic}} = R_{P_{CO_2}} + R_{H^+} + R_{\text{Phy}} + S_{Na^+} \tag{5}$$

where $R_{P_{CO_2}}$ refers to increased partial pressure of CO_2 within the root zone; R_{H^+} is enhanced proton (H^+) released in the root zone in case of certain crops that include legumes; R_{Phy} addresses physical effects of roots in improving soil aggregation and hydraulic properties of the root zone; and S_{Na^+}represents Na^+ content of shoot, which is removed through harvest of the aerial plant portion. The collective effects of these factors ultimately lead to soil amelioration, provided drainage is present and adequate leaching occurs (Fig. 2).

4.2.1. Partial pressure of CO_2 in the root zone

Dissolution and precipitation kinetics of calcite are determined by the chemistry of the system. A typical reaction for the dissolution of calcite may be expressed as a function of CO_2 in the root zone:

$$CaCO_3 + CO_2 + H_2O \Leftrightarrow Ca^{2+} + 2HCO_3^- \tag{6}$$

The reaction presented in Eq. (6) summarizes three processes (Dreybrodt, 1992), which occur concurrently: (1) conversion of CO_2 in an aqueous matrix, such as soil solution, into H_2CO_3 and its reaction with $CaCO_3$ as given in Eq. (7); (2) dissociation of H_2CO_3 into H^+ and HCO_3^- and the reaction of H^+ with $CaCO_3$ as presented in Eq. (8); and (3) dissolution of $CaCO_3$ resulting in Ca^{2+} and CO_3^{2-} as shown in Eq. (9):

$$CaCO_3 + H_2CO_3 \Leftrightarrow Ca^{2+} + 2HCO_3^- \tag{7}$$
$$CaCO_3 + H^+ \Leftrightarrow Ca^{2+} + HCO_3^- \tag{8}$$
$$CaCO_3 + H_2O \Leftrightarrow Ca^{2+} + CO_3^{2-} + H_2O \tag{9}$$

The dissolution of $CaCO_3$ through the above reactions results in the release of Ca^{2+}, HCO_3^-, and CO_3^{2-} to the soil solution. Due to the low solubility of calcite in water, the reaction presented in Eq. (9) yields a minor amount of Ca^{2+} through mineral hydrolysis process. The reactions represented in Eqs. (7) and (8) occur concurrently with a major contribution to the enhanced dissolution of calcite.

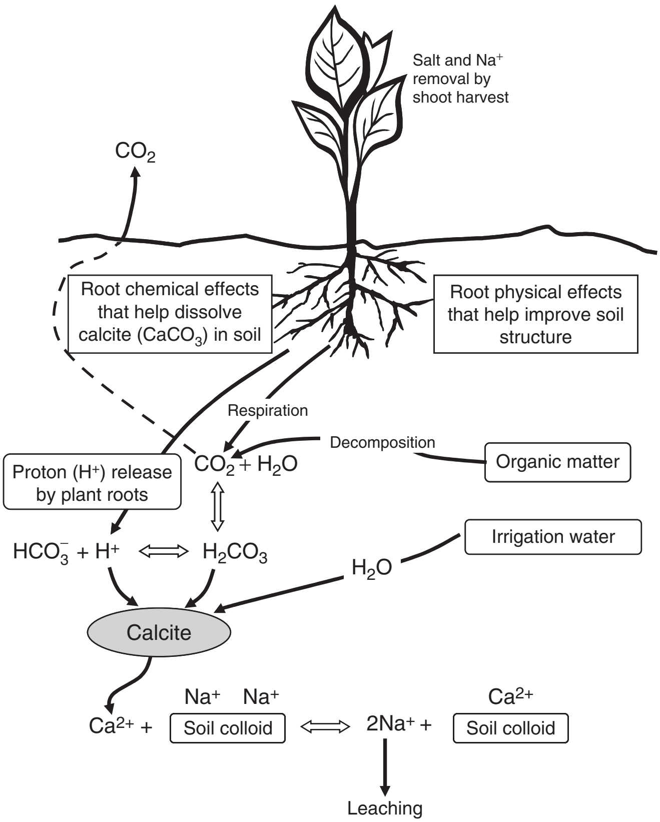

Figure 2 Schematic illustration of driving forces for phytoremediation of calcareous sodic and saline-sodic soils: increased partial pressure of CO_2 within the root zone; enhanced proton (H^+) release in the root zone in case of certain crops; physical effects of roots in improving soil aggregation and hydraulic properties of the root zone; and salt and sodium (Na^+) content of shoot, which is removed through harvest of aerial plant portion.

In aerobic soils, P_{CO_2} may increase to a maximum level of 1 kPa, which is equivalent to 1% of the soil air by volume (Nelson and Oades, 1998) and much higher under anaerobic conditions of flooded soils (Narteh and Sahrawat, 1999; Ponnamperuma, 1972) where saturated conditions inhibit the escape of CO_2 to the atmosphere. Such retention of CO_2 increases P_{CO_2} in the soil. Similarly, P_{CO_2} in the root zone is enhanced by root respiration under cropped conditions (Robbins, 1986a). In noncalcareous soils, an increase in CO_2 results in the production of H^+ and a corresponding reduction in soil pH. However, pH usually does not decrease to a great extent in calcareous soils (Nelson and Oades, 1998), since changes in pH are buffered by the enhanced dissolution of calcite (Van den Berg and

Loch, 2000). Therefore, increased levels of P_{CO_2} in calcareous sodic and saline-sodic soils result in enhanced dissolution of calcite thereby providing adequate levels of Ca^{2+} for soil amelioration.

Root respiration is not the only mechanism influencing P_{CO_2} in the root zone. It is also affected by the following mechanisms that can act individually or collectively: (1) production of CO_2 from oxidation of plant root exudates as soil organisms assist in producing CO_2 when they oxidize polysaccharides, proteins, and peptides; and (2) production of organic acids by soil organisms, which help in dissolving calcite. Regardless of the source of CO_2 production in soils, whether it be from respiring roots, decomposing organic matter and root exudates, or organic acid dissolution of calcite, the end result is the same: Ca^{2+} becomes available to replace exchangeable Na^+ at a much higher rate than can be achieved by dissolution of calcite at the level of P_{CO_2} in the atmosphere.

Some studies on phytoremediation of calcareous sodic soils have quantified the levels of P_{CO_2} produced under different crops. Robbins (1986a) measured P_{CO_2} in the root zone of several crops during the amelioration of a calcareous sodic soil ($pH_s = 8.6$, $EC_e = 2.4$ dS m^{-1}, ESP = 33) packed in lysimeters. The crops evaluated for the quantification of P_{CO_2} levels in the root zone were barley, alfalfa, cotton, tall wheat grass [*Agropyron elongatum* (Host) Beauv.], and a sorghum-sudan grass hybrid called sordan [*Sorghum* × *drummondii* (Steud.) Millsp. & Chase]. There was also a set of noncropped treatments consisting of a control, the application of fresh manure at 5 kg m^{-2} soil (50 Mg ha^{-1}), and the addition of gypsum at 5 kg m^{-2} soil (50 Mg ha^{-1}). The soil atmosphere samples collected from the root zone at different time intervals indicated that among the cropped treatments, cotton had the lowest P_{CO_2} values (<3.6 kPa). Sordan produced the highest levels of P_{CO_2} reaching 14 kPa (Table 4). Sodium removal efficiencies as measured in leachates collected from the cropped treatments were found directly proportional to the corresponding levels of P_{CO_2} in the soil (Robbins, 1986b). Analysis of the postamelioration soil samples revealed the amelioration effect of the cropped treatments throughout the root zone. This was particularly applicable in case of sordan. In the noncropped gypsum-treated lysimeters, the greatest amelioration occurred within the top 0.2 m of the soil, the layer in which the amendment was incorporated to ameliorate the soil. The hydraulic conductivity of the gypsum-treated soil declined to near zero after the passing of one pore volume of drainage water. Contrasting this, the hydraulic conductivity in the lysimeters cropped with sordan was maintained at an adequate level throughout the study period.

In another phytoremediation study conducted in lysimeters, Qadir *et al.* (1996a) leached columns of a calcareous saline-sodic soil ($pH_s = 9.1$, $EC_e = 9.8$ dS m^{-1}, SAR = 103) cropped with Kallar grass. Leaching cycles were undertaken during early, peak, and slow growth periods of the grass. Similar leaching schedules were practiced in three noncropped treatments,

Table 4 Mean values for net Na^+ removal ($\pm$ standard error) in various cropped and noncropped treatments as a function of partial pressure of CO_2 (P_{CO_2}) in a lysimeter experiment (modified from Robbins, 1986a)

Treatment	P_{CO_2} (kPa)[a]	Na^+ removal (mol)[b]
Control[c]	0.9–4.3	1.0 ± 0.1
Gypsum[d]	0.9–2.4	3.3 ± 0.3
Manure[e]	3.1–6.0	1.6 ± 0.2
Cotton (*Gossypium hirsutum* L.)	3.0–3.6	1.4 ± 0.1
Alfalfa (*Medicago sativa* L.)	4.8–7.2	2.6 ± 0.2
Sordan [*Sorghum* × *drummondii* (Steud.) Millsp & Chase]	5.8–14.1	4.0 ± 0.3

[a] The P_{CO_2} values fluctuated during the experimental period. The highest values in the cropped treatments were obtained during vigorous vegetative growth.
[b] Initially there were 7.5 mol of Na^+ (soluble and exchangeable) in each soil column.
[c] Without crop or chemical amendment application.
[d] Gypsum applied at 5 kg m^{-2} soil and incorporated in 0–0.2 m.
[e] Fresh manure applied at 5 kg m^{-2} soil and incorporated in 0–0.2 m.

which consisted of a control (without gypsum) and two receiving gypsum at 50% and 100% gypsum requirement (GR) to remediate the soil. The rate of Na^+ removal in the grassed treatment during its early growth stages (3.3 mmol day^{-1}) was less than that with control (4.7 mmol day^{-1}). However, the rate of Na^+ leaching increased substantially to a maximum of 16.2 mmol day^{-1} during peak growth of the grass, which was comparable to that from the soil columns treated with gypsum at 100% GR (19.3 mmol day^{-1}). The rate of Na^+ removal in the grassed lysimeters again decreased (4.6 mmol day^{-1}) when leaching was undertaken during a subsequent period of slow growth. This suggests that the critical time for leaching of Na^+ from the soil during phytoremediation should be undertaken during periods of vigorous plant growth so as to take advantage of increased calcite solubility associated with an increase in the P_{CO_2} in the root zone. Since soils remain at or near saturation during leaching events, CO_2 diffusion from the soil surface is greatly reduced. Hence, leaching when P_{CO_2} is at its highest levels would result in the entrapment of the maximum amount of CO_2 leading to a substantial increase in the rate of calcite dissolution.

Bauder and Brock (1992) evaluated alfalfa, barley, and sordan—alone and in combination with surface-applied chemical amendments—to mitigate the impacts of long-term irrigation of fine loamy, calcareous soils from waters of various combinations of low and high salinity and sodicity levels. They essentially concluded that C_3 (grass-type) crops, which produce relatively significant amounts of soil atmosphere CO_2 facilitated the leaching of Na^+ as a consequence of minor acidification of the soil solution.

In a modeling study, Simunek and Suarez (1997) predicted that sodic soil amelioration with calcite was feasible, but the time and quantity of water required for amelioration to increase the P_{CO_2} to 2 kPa to increase dissolution of calcite was approximately two times greater than that required for amelioration with gypsum. In a more recent evaluation, Suarez (2001) simulated a similar time and quantity of water for calcite dissolution at P_{CO_2} of 5 kPa. As determined by Robbins (1986b), crops such as cotton producing root zone P_{CO_2} in this range (3.0–3.6 kPa) may need greater time and quantity of water than required for chemical soil amelioration. However, using crops for phytoremediation that produce P_{CO_2} as high as 14 kPa in the root zone as in the case of sordan, the requirement for water and time would be greatly reduced. Thus, a leaching strategy for calcareous sodic and saline-sodic soils under cropping with high P_{CO_2} in the root zone would result in significant savings in the amount of water required and therefore a decrease in the drainage volume.

Although soil atmosphere data from lysimeter experiments may not represent field conditions, such information provides an insight into P_{CO_2} data under controlled conditions. The P_{CO_2} data show considerable CO_2 production differences between crop species at different plant growth stages, and the amount of irrigation water required to leach Na^+. If the differences in CO_2 production by different crops and crop management are known, it may well be possible to select crops and management practices that would enhance Na^+ removal from the cation exchange complex more efficiently than has been achieved before.

4.2.2. Proton release by plant roots

The release of H^+ from plant roots is considered as a process contributing to a decrease in pH of the rhizosphere. Several studies have shown that various plant species supplied with ammonium (NH_4^+) nutrition acidify their rhizosphere, whereas the species alkalize it when nitrate (NO_3^-) is supplied as a nitrogen (N) source (Marschner and Römheld, 1983; Schubert and Yan, 1997). In addition, legumes relying on symbiotic N_2 fixation have been shown to acidify their rhizosphere (Schubert *et al.*, 1990b). Although considerable H^+ extrusion has been recorded in the rhizosphere of various N_2-fixing plant species (Hinsinger, 1998; Marschner and Römheld, 1983; Nye, 1981; Schubert *et al.*, 1990a), this biological acidification mechanism has been studied mainly in acidic soils rather than its possible role in the remediation of sodic and saline-sodic soils. Protons released by N_2-fixing plant species in the root zone of sodic soils assist in calcite dissolution resulting in Ca^{2+} and HCO_3^-. This chemical reaction is the same as in the case of enhanced P_{CO_2} in the root zone as shown in Eq. (8).

The release of H^+ by plants at the soil–root interface results in an electrochemical gradient. Cation uptake increases net H^+ release through partial depolarization of the membrane potential, which facilitates active

H^+ pumping (Schubert and Yan, 1997). Due to H^+ release cytosolic pH increases, which triggers organic anion synthesis. The organic anion complement of a crop or the litter component of trees is thus a measure of net H^+ release at the root–soil interface that has been named ash alkalinity (Jungk, 1968). Ash alkalinity has been routinely measured on several crops, forages, and tree species to assess their acidification potential (Moody and Aitken, 1997; Noble and Randall, 1999; Noble *et al*., 1996).

In a comprehensive evaluation of ash alkalinity of 106 plant species in the semiarid tropics of northern Australia, Noble and Nelson (2000) observed a range of values from 25 to 347 $cmol_c\ kg^{-1}$ for *Themeda triandra* and *Brunoniella acaulis*, respectively. While the range of ash alkalinity varies considerably among species, there appears to be little variability within a species. For example, in an assessment of the ash alkalinity of a range of legume species adapted to the wet and semiarid tropics, variation in ash alkalinity between accessions of the same species was relatively low while among species there was a greater degree of variation. It would appear that there is a link between adaptation to a specific agroecotype and ash alkalinity. For example, *Calliandra calothyrsus*, a species well adapted to highly weathered soils of the wet tropics, had the lowest ash alkalinity (44 $cmol_c\ kg^{-1}$) while *Stylosanthes seabrana*, a species well adapted to heavy-textured base-rich soils of the semiarid tropics, had an ash alkalinity value of 125 $cmol_c\ kg^{-1}$, three times greater than that of *C. calothyrsus*. Intuitively one could hypothesize that plant species that have evolved on soils of high base status may have a high ash alkalinity and hence a greater propensity to generate H^+ at the root–soil interface. Therefore, the measurement of ash alkalinity in species that are adapted to sodic soil conditions could be used to select the most appropriate species to enhance the rate of calcite dissolution through H^+ release in the root zone. In several studies undertaken to measure ash alkalinity over a wide range of plant species, a highly significant relationship between the Ca^{2+} concentration in plant material and ash alkalinity has been observed suggesting a simple and practical surrogate for the measurement of this attribute (Fig. 3).

In order to maximize the benefits of net acid addition in sodic and saline-sodic soils through growing species with high ash alkalinity, a key component would be the removal of as much aboveground biomass as possible (Yan and Schubert, 2000). In a study quantifying the net acid addition rate (NAAR) associated with *Stylosanthes*-based legume systems in the semiarid tropics of northern Australia, extensive grass/legume-based pasture systems were found to have a NAAR of 0.2 kmol $H^+\ ha^{-1}\ year^{-1}$ (Noble *et al*., 1997). Contrasting this, in a *Stylosanthes* seed production system where the entire aboveground biomass was removed from the field for processing, there was a large increase in NAAR (10.6 kmol $H^+\ ha^{-1}\ year^{-1}$) with an equivalent value of 530 kg $CaCO_3\ ha^{-1}\ year^{-1}$. This evidence clearly demonstrated the association of greater rate of acid addition with highly exploitive production systems. This aspect has yet to be fully understood and

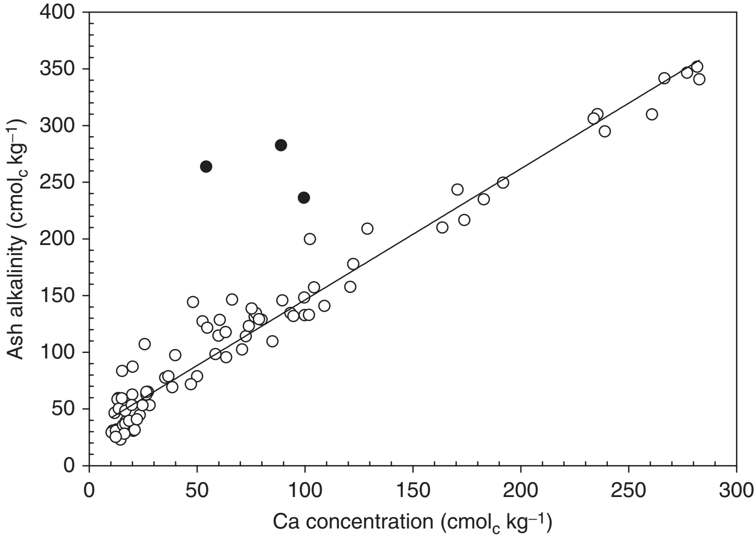

Figure 3 Relationship between calcium (Ca^{2+}) concentration in plant material and ash alkalinity. The outliers (closed circles) are from *Salsola kali* and two collections of *Portulaca oleracea*. Regression equation for ($n = 93$): $y = 30.52 + 1.15x$; $r^2 = 0.958$ does not include the three outliers [adapted from Noble and Nelson (2000)].

appreciated in the context of H^+ release by the roots and phytoremediation of sodic, saline-sodic, and alkali soils.

Limited information is available on the contribution of H^+ release by the roots of legume plant species to the phytoremediation process of calcareous sodic and alkali soils. In a lysimeter study on a calcareous sodic soil ($pH_s = 7.4$, $EC_e = 3.1$ dS m^{-1}, ESP = 27.6), Qadir *et al.* (2003a) evaluated alfalfa without N supplement (relying on N_2 fixation) with that relying on ammonium nitrate (NH_4NO_3) nutrition. Despite the fact that both the treatments produced statistically similar root and shoot biomass, there was 8% greater removal of Na^+ in the leachate collected from the soil columns grown with N_2-fixing alfalfa (Table 5). This evidence indicated dissolution of an additional amount of calcite in the N_2-fixing treatment, suggesting that the amelioration rate of calcareous sodic soils could be increased by means of crop management conducive for the release of greater amount of CO_2 and H^+ in the root zone. In addition, using appropriate N_2-fixing crops as a phytoremediation tool has the advantage of enhanced availability of N in the soil for the postamelioration crops.

4.2.3. Physical effects of roots

Plant roots are essential for maintaining soil structure, and the presence of roots at the lower depths of the soil profile drives the processes of macropore formation. Plant roots improve soil porosity by creating either biopores or

Table 5 Shoot and root dry matter production and cumulative Na^+ removal (± standard error) in phytoremediation treatments from a calcareous sodic soil in a lysimeter experiment (modified from Qadir *et al.*, 2003a)

Treatment	Shoot (g lysimeter^{-1})	Root (g lysimeter^{-1})	Na^+ removal (mmol)
N_2-fixing alfalfa (*Medicago sativa* L.)[a]	31.2 ± 0.9 a	12.0 ± 0.3 a	26.1 ± 0.4 a
NH_4NO_3-fed alfalfa (*Medicago sativa* L.)[b]	30.2 ± 0.3 a	11.8 ± 0.1 a	24.2 ± 0.5 b

[a] Inoculated with rhizobium (*Rhizobium meliloti*, strain No. 6052).
[b] Supplied with mineral N (100 mg kg^{-1} soil at sowing + 50 mg kg^{-1} soil 12 days after sowing).
Means followed by the same letter within a column are not statistically different ($p = 0.05$).

structural cracks (Czarnes *et al.*, 2000; Oades, 1993; Pillai and McGarry, 1999; Yunusa and Newton, 2003). In addition, roots stimulate changes in the root zone through removal of entrapped air from larger conducting pores and generation of alternate wetting and drying cycles. Aggregate stability is enhanced because of *in situ* production of polysaccharides and fungal hyphae in conjunction with differential dewatering at the root–soil interface (Boyle *et al.*, 1989; Tisdall, 1991). In addition, roots of some crops act like a potential tillage tool as they can grow through compacted soil layers and improve the soil below the plow pan (Elkins *et al.*, 1977).

Plant roots play an important role in facilitating the process of leaching Na^+, replaced from the cation exchange complex, to the deeper soil layers. This process can be triggered by deep-rooted vegetation that can withstand ambient levels of salinity and sodicity during phytoremediation. This is consistent with the observation that deep-rooted perennial grasses and legumes can improve structure of the plow layer (Tisdall, 1991) with concurrent improvement in hydraulic properties of sodic soils (Akhter *et al.*, 2004; Ilyas *et al.*, 1993).

Observations from field studies reveal the beneficial effects of root growth in sodic soils during phytoremediation. Ilyas *et al.* (1993) tested different phytoremediation treatments—deep-rooted alfalfa, and sesbania-wheat (*Triticum aestivum* L.)-sesbania rotation—alone and in conjunction with the application of gypsum to ameliorate a low-permeability hard saline-sodic soil ($pH_s = 8.8$, $EC_e = 5.6$ dS m^{-1}, SAR = 49) in the Indus Plains of Pakistan. Alfalfa grown for 1 year resulted in a twofold increase in saturated hydraulic conductivity (K_s). The original K_s values in the upper 0.8 m of soil ranged from 0.8 to 1.5×10^{-7} m s^{-1}. Alfalfa roots penetrated as deep as 1.2 m in the gypsum-treated plots as compared to 0.8 m in untreated plots. Other phytoremediation treatment, sesbania-wheat-sesbania rotation, caused a similar increase in K_s up to 0.4 m depth (Table 6). Sesbania roots

Table 6 Phytoremediation and gypsum effects on field-saturated hydraulic conductivity (K_s) of a saline-sodic soil after 1 year (modified from Ilyas *et al.*, 1993)

Treatment	Hydraulic conductivity (K_s) ($\times 10^{-7}$ m s^{-1}) Soil depth increment (m) 0.0–0.2	0.2–0.4	0.4–0.6	0.6–0.8
	Without gypsum application			
Alfalfa	2.4 ab[a]	3.8 a	2.0 a	3.4 a
Wheat straw added at 7.5 Mg ha^{-1}	1.8 b	1.4 b	1.1 a	1.1 a
Sesbania-wheat-sesbania	3.4 a	1.9 b	1.9 a	1.7 a
Fallow	1.2 b	1.1 b	1.6 a	2.6 a
	Gypsum applied at 25 Mg ha^{-1}			
Alfalfa	6.5 a	3.9 a	4.4 a	4.2 a
Wheat straw added at 7.5 Mg ha^{-1}	3.5 b	2.1 b	1.8 b	2.9 ab
Sesbania-wheat-sesbania	7.9 a	2.0 b	1.8 b	2.1 b
Fallow	2.9 b	1.2 b	1.2 b	1.5 b

[a] Means followed by the same letter within a column and gypsum treatment are not statistically different ($p = 0.05$).

were healthy, thick, and well branched, but grew only to a depth of 0.3 m. Other options attempted were physical manipulation of the same soil, but they did not improve soil permeability to an appreciable extent. These options were subsoiling (by curved chisels to a depth of 0.45 m at 0.5 m intervals) and open-ditch drains (1 m deep). In another field study on a duplex soil in Australia, Cresswell and Kirkegaard (1995) found that the inclusion of crops such as canola (*Brassica napus* L.) in cereal rotations did not improve porosity of the dense B-horizon. They proposed inclusion of deep-rooted crops such as alfalfa to mixed cropping systems as a potential biological drilling strategy to improve subsoil permeability.

Akhter *et al.* (2004) evaluated the impact of growing Kallar grass over different periods (from 1–5 years) on different soil properties such as available water content, bulk density, porosity, and K_s of a saline-sodic field ($pH_s = 10.4$, $EC_e = 22.0$ dS m^{-1}, SAR = 184). The preamelioration K_s value was 0.035 mm day^{-1} (0.4×10^{-9} m s^{-1}) in the upper 0.2 m of soil. The K_s increased substantially within 5 years to a final value of 55.6 mm day^{-1} (6.4×10^{-7} m s^{-1}); this increase was significantly correlated with increases in porosity and water retention. In addition, the K_s increase was accompanied by a reduction in soil bulk density, which fell from an average value of 1.62 to 1.53 Mg m^{-3} over the same period (Table 7). Soil porosity, on the other hand, increased from 38.9% to 42.8%. These changes were probably due to the fact that Kallar grass has an extensive root system, which can penetrate the soil to a depth of 1 m (Malik *et al.*, 1986).

Table 7 Effect of various phytoremediation treatments (growing of kallar grass for different time periods) on the available water content, bulk density, porosity, and hydraulic conductivity (K_s) of the upper 0.2 m of a calcareous, saline-sodic soil ($pH_s = 10.4$, $EC_e = 22.0$ dS m^{-1}, SAR = 184) with sandy clay loam texture in a field (based on the data reported by Akhter *et al.*, 2004)

Treatment	Available water ($kg\,kg^{-1}$)	Bulk density ($Mg\,m^{-3}$)	Porosity (%)	K_s (mm day^{-1})[a]
Control (noncropped)	0.155	1.62	38.9	0.04
Kallar grass (1 year)	0.175	1.61	39.1	1.5[b]
Kallar grass (2 years)	0.184	1.58	40.4	9.0[b]
Kallar grass (3 years)	0.195	1.55	41.5	18.0[b]
Kallar grass (4 years)	0.216	1.54	42.3	38.0[b]
Kallar grass (5 years)	0.214	1.53	42.8	55.6

[a] 1 mm $day^{-1} = 1.16 \times 10^{-8}$ m s^{-1}.
[b] Estimated values from a graph of soil hydraulic conductivity (K_s) against time.

Although deep tillage has shown to be effective in ameliorating subsoils with low porosity, the benefits in some cases have been short lived (Cresswell and Kirkegaard, 1995). In addition, the high cost of deep tillage has restricted its large-scale adoption. As the roots of some plant species can act as potential tillage tools, biological drilling has shown promise as an alternative to deep tillage for the amelioration of dense subsoils (Elkins *et al.*, 1977). Biological drilling has two stages: (1) creation of macropores in the subsoil by the roots that penetrate the compacted soil layer as they decay, resulting in improved water movement and gaseous diffusion; and (2) benefits for the subsequent crop(s) after improvements in subsoil macroporosity (Cresswell and Kirkegaard, 1995; Elkins, 1985). For example, the roots of some crops such as Bahia grass (*Paspalum notatum* Flügge) and tall fescue [*Festuca arundinacea* (L.) Schreb.] have been shown to grow through compacted soil layers with subsequent improvement of the soil below the plow pan. Field experimentation with tall fescue showed an advantage for large diameter roots of the species in penetrating low-permeability soils (Elkins *et al.*, 1977).

In addition to quantifying the effects of rooting systems of grasses and forage species during phytoremediation, studies have been conducted to evaluate the role of tree roots on physical properties of sodic soils (Garg, 1998; Mishra and Sharma, 2003; Mishra *et al.*, 2002). Mishra and Sharma (2003) evaluated 3-, 6-, and 9-year-old plantations of two leguminous tree species—*Prosopis juliflora* (Sw.) DC. and *Dalbergia sissoo* Roxb. ex. DC.—for their effects on the extent of changes in the physical properties of a sodic soil in India. The porosity of the soil increased and bulk density decreased with the age of plantations as compared to the respective control plots where no tree was grown. The control corresponding to the 9-year-old *P. juliflora* and *D. sissoo* plantations had 40.4% and 44.5% porosity in the surface soil, which increased to 46.9% and 51.0% after 9 years of their growth, respectively. The mean soil permeability in the upper 0.1 m soil depth increased with the age of the plantation. Nine years after planting, the mean soil permeability increased from 0.24×10^{-10} to 10.95×10^{-10} cm^2 in the *P. juliflora* plantation and from 0.37×10^{-10} to 11.69×10^{-10} cm^2 in the *D. sissoo* plantation. Soil bulk density was maximum in control plots and reduced after afforestation in case of both tree species with nonsignificant treatment differences. The improvement in soil physical properties was attributed to increased levels of organic matter that improved aggregation of soil particles, resulting in the development of suitable soil structure.

4.2.4. Salt and Na^+ uptake by shoots

Removal of aboveground biomass of plant species, used for phytoremediation of sodic and saline-sodic soils, removes salts and Na^+ taken up by the plants and accumulated in their shoots. Highly salt-resistant species such as halophytes may accumulate quite high levels of salts and Na^+ in their shoots. For example, *Atriplex* species grown under rangeland conditions have leaf ash concentrations 130–270 g salts kg^{-1} (Hyder, 1981) and if grown in salt-affected soils, the species can have leaf ash concentrations as high as 390 g salt kg^{-1} (Malcolm *et al.*, 1988). Despite these high levels of salt removal via shoot harvest of the plant species, such salt removal alone does not play a significant role in the amelioration process of salt-affected soils, which contain huge amounts of salts. For example, Barrett-Lennard (2002) predicted that under nonirrigated conditions, halophytic crops with an annual productivity of about 10 t ha^{-1} and 25% shoot salt concentration on dry weight basis (250 g kg^{-1}) would require about 20 consecutive years to remove half of the initial content of salts (86 Mg ha^{-1}) present in 2 m depth of a salt-affected soil. It must be noted that under nonirrigated conditions, fodder shrubs such as *Atriplex* species rarely produce more than 2 Mg ha^{-1} annually (Barrett-Lennard *et al.*, 1990). In addition, a major fraction of salts that accumulates in leaves is recycled back to the soil in the form of leaf fall. Therefore, the effects of growth and salt uptake by halophytes on reduction in soil salinity and sodicity are likely to be minimal under nonirrigated conditions.

Under irrigated conditions, which are a prerequisite for enhanced calcite dissolution and subsequent removal of Na^+ from the root zone during phytoremediation of sodic soils, the contribution of typical salt

Table 8 Shoot dry matter and removal of salt and Na^+ in the aboveground harvest of some plant species (modified from Gritsenko and Gritsenko, 1999)

Plant species[a]	Shoot dry matter ($Mg\ ha^{-1}$)	Salt removal ($kg\ ha^{-1}$)	Na^+ removal ($kg\ ha^{-1}$)
Japanese millet	8.2	224	46
Amaranth	5.0	182	3
Sunflower	9.1	172	4
Sudan grass	5.0	72	2
Alfalfa	11.3	178	26

[a] Japanese millet [*Echinochloa esculenta* (A. Braun) H. Scholz], amaranth [*Amaranthus cruentus* L.], sunflower [*Helianthus annuus* L.], Sudan grass [*Sorghum* × *drummondii* (Steud.) Millsp. & Chase], alfalfa (*Medicago sativa* L.).

accumulators through shoot harvest to net removal of salt and Na^+ is minimal (Table 8). The reasons for this are that, besides native soil salinity and sodicity, salts and Na^+ are also added to sodic soils during irrigation, particularly in cases where the irrigation waters are already saline and/or sodic. For example, Kallar grass is grown on calcareous sodic and saline-sodic soils as a potential phytoremediation crop in several parts of the world. Its aboveground vegetation (forage) contains salt levels in the range of 40–80 g kg^{-1} when grown in soils with salinity levels of about 20 dS m^{-1}. Considering annual forage production of the grass of ~25 Mg ha^{-1}, the volume of irrigation water required to grow the grass is estimated to be 10^4 m^3 ha^{-1} (10^7 liter ha^{-1}). If the irrigation water has a salinity level 1.5 dS m^{-1}, which is typical of most waters used for irrigation, the amount of salt added in irrigation water would be equivalent to 9.6 Mg ha^{-1} compared with 1–2 t ha^{-1} of salt removed in forage. The estimates of Gritsenko and Gritsenko (1999) reveal that Na^+ uptake by aboveground biomass of several plant species constitutes 2–20% of the total salt uptake (Table 8). In an evaluation, Qadir *et al.* (2003b) found that Na^+ removal by shoot harvest of crops such as alfalfa would contribute to only 1–2% of the total Na^+ removed during phytoremediation of sodic soils. Therefore, the principal source of sodicity decrease through phytoremediation of calcareous sodic soils is leaching of salts and Na^+ from the root zone to deeper soil depths rather than removal by harvesting the aboveground plant biomass.

4.3. Comparative efficiency of phytoremediation

The efficiency of different plant species used in phytoremediation of sodic and saline-sodic soils has been found to be highly variable. In general, the species with greater production of biomass together with the ability to withstand ambient soil salinity and sodicity as well as periodic inundation have been found to be efficient in soil amelioration (Kaur *et al.*, 2002; Qadir *et al.*, 2002).

Phytoremediation has two major advantages for the farmers: (1) no financial outlay to purchase chemical amendments, and (2) accrued financial or other farm-level benefits from crops grown during amelioration.

Several studies involving phytoremediation and other approaches aimed at the improvement in sodic soils have been carried out in various parts of the world (Ahmad *et al.*, 1990; Ghaly, 2002; Kumar and Abrol, 1984; Robbins, 1986b). In addition to the ameliorative effects on soil sodicity, these approaches have been compared for their effects on the nutrient availability status in the postamelioration soil, zone of amelioration in terms of soil depth, and environment conservation in terms of C sequestration (Bhojvaid and Timmer, 1998; Garg, 1998; Kaur *et al.*, 2002).

4.3.1. Soil sodicity amelioration

Various evaluations in the field have revealed that chemical amelioration and phytoremediation approaches perform similarly in terms of their ability to decrease the soil sodicity levels. Results of a field experiment (Kumar and Abrol, 1984) conducted on a barren, calcareous, and alkali soil ($pH_{1:2}$ = 10.6, $EC_{1:2}$ = 2.7 dS m^{-1}, ESP = 94) indicated that the amelioration efficiency of two grasses, Para grass [*Brachiaria mutica* (Forssk.) Stapf.] and Karnal grass, was comparable with soil application of gypsum at 12.5 Mg ha^{-1} (Table 9). The yield of the first rice crop in the gypsum treatment averaged 3.7 Mg ha^{-1} as compared to 3.8 and 4.1 Mg ha^{-1} from the treatments cropped for 1 year with Para and Karnal grasses, respectively. The corresponding rice yields after 2 years of grass cropping were 5.3 and 6.1 Mg ha^{-1}. Hamid *et al.* (1990) evaluated the amelioration efficiency of Kallar grass during different periods of root decay. They leached a calcareous, silty clay loam, saline-sodic field (pH_s = 8.3–9.3, EC_e = 16.8–37.5 dS m^{-1}, SAR = 32.5–108.9) 3, 6, 9, and 12 days after each harvest during 2 years of grass

Table 9 Effect of gypsum and grass-based cropping systems on grain yields of first rice and wheat crops after gypsum application or after completion of Para or Karnal grass cultivation on an alkali soil (modified from Kumar and Abrol, 1984)[a,b]

Treatment	Rice yield (Mg ha^{-1})	Wheat yield (Mg ha^{-1})
Rice-wheat rotation (without gypsum)	0.00	0.00
Gypsum (12.5 Mg ha^{-1}) + Rice-wheat	3.70	2.60
Para grass grown for 1 year	3.80	0.13
Para grass for grown 2 years	5.30	2.56
Karnal grass for grown 1 year	4.10	0.26
Karnal grass for grown 2 years	6.10	3.41

[a] Initial soil $pH_{1:2}$ for the 0–0.15 m depth was 10.6.
[b] Initial soil $EC_{1:2}$ for the 0–0.15 m depth was 2.7 dS m^{-1}.

cultivation. Each plot was kept flooded for 3 days during leaching. The amelioration efficiency of Kallar grass was greater in the plots leached 6 days after harvesting, and it was comparable with the gypsum-treated soil.

In addition to Kallar grass, Ahmad *et al.* (1990) tested two plant species, sesbania and sordan, as phytoremediation treatments in a field study. The study compared the performance of these species with each other and with that of a commonly used gypsum application (13 Mg ha^{-1}) and a noncropped control in the context of a calcareous, sandy clay loam, saline-sodic field ($pH_s = 8.2$–8.6, $EC_e = 7.4$–9.0 dS m^{-1}, SAR = 55.6–73.0). The plant species were grown for two seasons (15 months). The efficiency of each treatment, as indicated by a decrease in SAR in the upper 0.3 m of soil, was as follows: gypsum (postamelioration SAR = 24.7) > sesbania (30.1) ≈ Kallar grass (32.5) > sordan (40.0) > control (57.2). Sesbania yielded the largest amount of seasonal forage, providing 40.8 Mg ha^{-1} of fresh biomass. In comparison with sesbania, smaller amounts of forage were yielded by Kallar grass (29.3 Mg ha^{-1}) and sordan (24.7 Mg ha^{-1}), indicating a direct relationship between forage production and decrease in soil sodicity.

In a later field experiment, Qadir *et al.* (1996a) compared four phytoremediation treatments—Kallar grass, sesbania, millet rice [*Echinochloa colona* (L.) Link], and finger millet [*Eleusine coracana* (L.) Gaertn.]—and a noncropped chemical treatment where gypsum was applied at 14.8 Mg ha^{-1}. The study was conducted on a calcareous, medium-textured, saline-sodic field ($pH_s = 8.4$–8.8, $EC_e = 9.6$–11.0 dS m^{-1}, SAR = 59.4–72.4). The effectiveness of each treatment, in terms of an observed decrease in soil SAR, was as follows: gypsum (postamelioration SAR = 28.2) > sesbania (33.5) > Kallar grass (36.9) > millet rice (42.6) > finger millet (48.1) > control without amendment or crop (53.2). The forage yield of each species was directly proportional to the subsequent reduction observed in soil sodicity (Table 10).

Some field trials on phytoremediation techniques have not been successful primarily because a salt-resistant crop was not the first crop in the rotation. Muhammed *et al.* (1990) compared phytoremediation (rice-wheat rotation), physical + phytoremediation (subsoiling by curved chisels to a depth of 0.5 ± 0.05 m at a chisel spacing of 1.2–1.5 m + rotation), chemical + phytoremediation (gypsum at 100% GR of the upper 0.15 m of soil + rotation), and chemical + physical + phytoremediation (gypsum + subsoiling + rotation) approaches to ameliorate two calcareous saline-sodic soils. Irrigation water (EC = 1.8 dS m^{-1}, SAR = 9.8) was applied according to the crop water requirement. The first crop in the rotation was rice, which was a complete failure and did not produce any grain on one soil (pH_s = 8.6–9.1, EC_e = 12.3–15.0 dS m^{-1}, ESP = 58.7–74.6), and a grain yield of 0.72 Mg ha^{-1} on the other soil (pH_s = 8.8–8.9, EC_e = 9.6–15.2 dS m^{-1}, ESP = 42.5–45.6). Four years after cropping, the average rice grain yield from both soils was in the order: chemical + phytoremediation (1.99 Mg ha^{-1}) > chemical + physical + phytoremediation (1.84 Mg ha^{-1}) > physical +

Table 10 Relationship between aboveground biomass production (Forage) by various plant species and relative decrease in soluble salt concentration of a saline-sodic field ($pH_s = 8.6 \pm 0.2$, $EC_e = 10.3 \pm 0.7$ dS m^{-1}, SAR $= 66 \pm 6$) (modified from Qadir *et al.*, 1996b)

Plant species			
Common name	Botanical name	Forage yield (Mg ha^{-1})	Final soil SAR
Sesbania	*Sesbania bispinosa* (Jacq.) W. Wight	32.3	33.5
Kallar grass	*Leptochloa fusca* (L.) Kunth	24.6	36.9
Millet rice	*Echinochloa colona* (L.) Link	22.6	42.6
Finger millet	*Eleusine coracana* (L.) Gaertn.	5.4	48.1
Gypsum (no crop)	—	—	28.2
Control (no crop)	—	—	53.2

phytoremediation (1.41 Mg ha^{-1}) > phytoremediation (1.02 Mg ha^{-1}). Chemical + phytoremediation and chemical + physical + phytoremediation treatments had similar values for the wheat grain yield (2.72 Mg ha^{-1}) followed by physical + phytoremediation (1.79 Mg ha^{-1}) and phytoremediation (1.46 Mg ha^{-1}). Within the upper 0.15 m soil depth, all the treatments decreased salinity (EC_e) to levels less than 5 dS m^{-1} and sodicity (ESP) to levels less than 22 on both the soils.

Several crop rotations have been evaluated to ameliorate sodic soils. Qadir *et al.* (1992) tested three irrigated crop rotations—sesbania-barley, rice-wheat, and Kallar grass-alfalfa—to ameliorate a calcareous saline-sodic field (pH_s = 8.1–8.2, EC_e = 9.2–13.7 dS m^{-1}, SAR = 30.6–42.7). All the crop rotations ameliorated the upper 0.15 m of soil after 1 year (SAR < 10) as did amelioration by the noncropped gypsum treatment (SAR < 14). Although initial salinity and sodicity levels of this field were closer to that used by Muhammed *et al.* (1990), there were three differences: (1) the soil was relatively coarser in texture, (2) the plots were irrigated with canal water (EC = 0.3 dS m^{-1}, SAR = 0.5), and (3) the irrigation water was applied in excess of crop water requirements to leach Na^+ to lower depths.

It is pertinent to note that growing of rice in submerged soils has been recognized as a component of technology for the amelioration of moderately sodic and saline-sodic soils and for keeping these soils productive during the remediation phase. In fact, combining phytoremediation (with or without gypsum addition) with lowland rice crop has been found to decrease Na^+ on the cation exchange complex along with facilitating the process of leaching the salts from the root zone. Under submerged condition of lowland rice, accumulated CO_2 has extended residence time in the soil atmosphere to react and neutralize alkalinity (Gupta and Abrol, 1990; Sahrawat, 1998; Van Asten, 2003).

In an evaluation of 17 experiments, carried out in different parts of the world, a comparable effect of chemical and phytoremediation approaches has been found in most cases (Fig. 4). The chemical treatment (application of gypsum in all experiments) resulted in a 60% decrease over initial sodicity levels (ESP or SAR) whereas a 48% decrease was calculated for the phytoremediation treatments. In some experiments, however, the phytoremediation approach was either unsuccessful or much less efficient than the

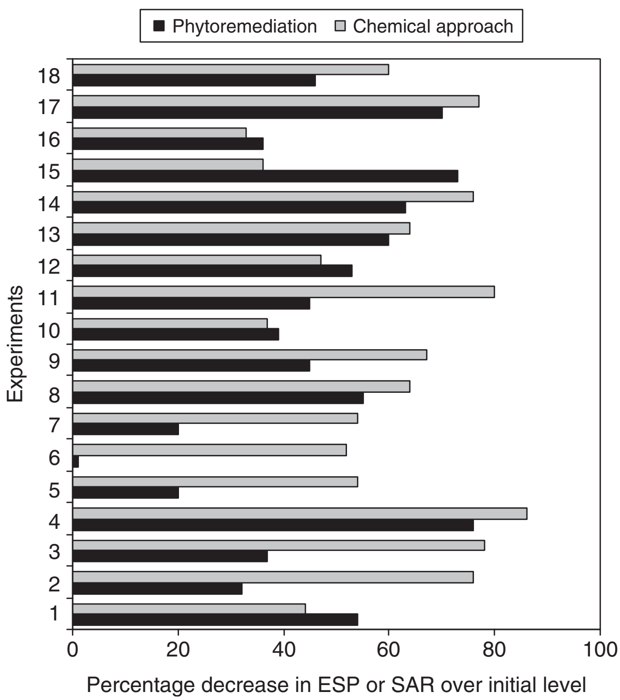

Figure 4 Summary of 17 experiments where chemical and phytoremediation treatments have been compared for their effects on a decrease in soil sodicity (SAR or ESP). The bars for respective treatments indicate percentage decrease over the respective levels of original soil SAR or ESP values. References to the experiment numbers are: 1 (Robbins, 1986a), 2 and 3 (Kausar and Muhammed, 1972), 4 (Qadir *et al.*, 1996b), 5 and 6 (Rao and Burns, 1991), 7 (Ahmad *et al.*, 2006), 8 (Singh and Singh, 1989), 9 (Ahmad *et al.*, 1990), 10 (Ilyas *et al.*, 1997), 11 (Kelley and Brown, 1934), 12 (Batra *et al.*, 1997), 13 and 14 (Muhammed *et al.*, 1990), 15 (Qadir *et al.*, 2002), 16 (Ghaly, 2002), 17 (Helalia *et al.*, 1992), and 18 (mean values of the 17 experiments). The experiments 1–7 were conducted in lysimeters, others under field conditions.

chemical treatment for the following four reasons: (1) a crop resistant to ambient soil salinity and sodicity levels was not the first in the crop rotation, (2) a phytoremediation crop was grown over a period that was not its most suitable growing season, (3) duration of time was not sufficient to exploit the potential impact of the phytoremediation crop, and/or (4) irrigation was not applied in excess of crop water requirement, which restricted the downward movement of Na^+ from the root zone. In general, phytoremediation worked well on moderately sodic and saline-sodic soils, provided: (1) irrigation was done in excess of crop water requirement to facilitate adequate leaching, and (2) the excess irrigation was applied when the crop growth and hence P_{CO_2} were at their peak. On such soils, the performance of phytoremediation was comparable with soil application of gypsum. On highly sodic and saline-sodic soils, use of chemical amendment outperformed phytoremediation treatments.

4.3.2. Zone of soil amelioration

The depth of sodic soil impacted by different amelioration approaches, that is anticipated zone of amelioration, is an important parameter to determine relative efficiency of these approaches. Phytoremediation and chemical approaches have been evaluated in terms of their effects on the depth of soil amelioration. In most comparative studies, amelioration in chemical treatments, gypsum in almost all cases, occurred primarily in the zone where the amendment was incorporated (Ilyas *et al.*, 1993; Qadir *et al.*, 1996a; Robbins, 1986b). Gypsum was mixed into the soil surface, and in most cases, it was agricultural grade and applied according to the GR of the upper 0.15 m of the soil. Only as amelioration approached completion in the region where gypsum was present, amelioration in the deeper depths began. This was a direct implication of the degree of Ca^{2+} saturation of the cation exchange sites relative to Na^+(Oster and Frenkel, 1980; Suarez, 2001).

In the case of phytoremediation of sodic and saline-sodic soils, amelioration occurs throughout the root zone. This has been commonly observed in these soils when grown with a range of crops. However, different crops caused variable degree and depth of soil amelioration, which was influenced by the morphology and volume of root and the depth of root penetration (Ahmad *et al.*, 1990; Akhter *et al.*, 2003; Ilyas *et al.*, 1993; Robbins, 1986b). Deep-rooted crops and those with tap root system have shown advantages in terms of greater depth of soil amelioration. For example, alfalfa roots can penetrate as deep as 1.2 m in the soil (Ilyas *et al.*, 1993).

4.3.3. Nutrient dynamics during soil amelioration

In addition to the beneficial effects on reducing salinity and sodicity levels in sodic and saline-sodic soils, phytoremediation provides additional benefits over other amelioration approaches, which do not provide such benefits, or at best to a lesser extent than phytoremediation. Improved nutrient availability of postamelioration soil is desirable for the growth of subsequent crops because nutritional problems occur in sodic soils, which range from deficiencies of several nutrients to the presence of phytotoxic levels of Na^+ and Cl^- (Naidu and Rengasamy, 1993).

Some studies have been conducted on nutrient behavior in sodic and saline-sodic soils during amelioration by phytoremediation and chemical approaches. Qadir *et al.* (1997) determined the availability of some macro- and micronutrients during amelioration of a calcareous saline-sodic soil ($pH_s = 8.2$–8.6, $EC_e = 7.4$–9.0 dS m^{-1}, SAR = 55.6–73.0). The phytoremediation treatments included the cropping of sesbania, sordan, or Kallar grass for 15 months. There was an increase in phosphorus (P), zinc (Zn), and copper (Cu) availability in the phytoremediation plots probably resulting from the production of root exudates and likely dissolution of some nutrient-coated calcite. Conversely, the noncropped gypsum treatment caused a decrease in the availability status of these nutrients. Besides leaching losses, adsorption of nutrients on some newly formed $CaCO_3$, a secondary consequence of gypsum dissolution, contributed to this decrease. Soil N content was decreased in all the treatments except for the N_2-fixing sesbania treatment where N content was increased from 0.49 to 0.53 g kg^{-1}. There was no treatment effect on soil potassium (K) availability since illite, a K-bearing mineral, was dominant in the clay fraction.

Ghai *et al.* (1988) reported that sesbania, grown for 45 days and used as green manure, enriched sodic soils by making up to 122 kg N ha^{-1} available to the rice crop which followed it. Studies using the ^{15}N isotope dilution technique have also provided evidence of N conservation by other phytoremediation crops such as Kallar grass (Malik *et al.*, 1986). When amelioration is undertaken on sodic soils using chemical amendments, some N loss may occur via NO_3^- leaching (Qadir *et al.*, 1997).

Soil microbial biomass is an agent of transformation for added and native organic matter and acts as a labile reservoir for several plant-available nutrients. The activity of microbial biomass is commonly used to characterize the microbiological status of a soil and to determine the effects of agricultural practices on soil microorganisms. Dehydrogenase activity (DHA) in soils is related to microbial populations, respiration activity, and soil organic matter, and provides an index of the overall microbial activity (Włodarczyk *et al.*, 2002). This parameter has been studied in experiments dealing with sodic soil amelioration through chemical and biological means. Batra *et al.* (1997) determined DHA and microbial biomass carbon (MBC) after using various combinations of chemical and phytoremediation treatments, which consisted of Karnal grass grown for 1 or 2 years (harvested biomass removed or left to decompose on the soil surface), gypsum application (at 14 Mg ha^{-1}) + Karnal grass, gypsum + sorghum, gypsum + rice, and gypsum + sesbania. The soil on which these treatments were applied was alkali ($pH_{1:2} = 10.6$, $EC_{1:2} = 2.1$ dS m^{-1}, ESP = 95, DHA = 4.5 μg triphenylformazan g^{-1}, MBC = 56.7 mg kg^{-1}). The levels of DHA in postamelioration soil were greater (118.7 μg triphenylformazan g^{-1}) in the phytoremediation treatments than gypsum + crop treatments (96.1 μg triphenylformazan g^{-1}). The MBC values were greater in gypsum + crop treatments (206.3 mg kg^{-1} soil) than in the cropped treatments (161.7 mg kg^{-1} soil). The overall average MBC (184 mg kg^{-1} soil) for all the treatments was more than three times the initial level of 56.7 mg kg^{-1} soil. In an earlier study, Rao and Ghai (1985) reported that permanent vegetation such as grasses caused significant increases in urease and dehydrogenase activities in alkali soils. Rao and Pathak (1996) reported an increase in urease and dehydrogenase activities after green manuring an alkali soil with sesbania.

In a 20-year study involving several tree plantations on an alkali soil (pH = 10.2–10.5), Singh and Gill (1990) found a considerable decrease in pH and increase in organic matter (organic C) content, and available levels of P and K of surface 0.15 m soil. The tree species included *P. juliflora* (Sw.) DC., *Acacia nilotica* (L.) Willd. ex Delile, *Eucalyptus tereticornis* Sm., *Albizia lebbeck* (L.) Benth., and *Terminalia arjuna* (Roxb. ex DC.) Wight & Arn. (Table 11).

4.3.4. Environment conservation

Sodic and saline-sodic soils have lost a large fraction of their original carbon (C) pool (Lal, 2001). The magnitude of the loss may range between 10 and 30 Mg C ha^{-1}, depending on the antecedent pool and the severity of degradation. The soil C pool is not only important for the soil to perform its productivity and environmental functions, but also plays an important role in the global C cycle (Lal, 2004). In addition to the amelioration effect,

Table 11 Ameliorative effect of 20-year-old tree plantations on pH, organic carbon (OC), and available P and K of the upper 0.15 m of an alkali soil in India (modified from Singh and Gill, 1990)

Tree species	$pH_{1:2}$	Organic C (g kg^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
Acacia nilotica (L.) Willd. ex Delile	8.4	8.5	59	499
Eucalyptus tereticornis Sm.	8.5	6.6	33	359
Prosopis juliflora (Sw.) DC.	7.5	9.3	111	702
Terminalia arjuna (Roxb. ex DC.)	7.9	8.6	68	410
Albizia lebbeck (L.) Benth.	7.9	6.2	43	387
Prestudy soil status	10.2	2.2	28	278

cultivation of appropriate crops, shrubs, and trees on sodic and saline-sodic soils has the potential to mitigate the accelerated greenhouse effect by increasing soil C through biomass production (Bhojvaid and Timmer, 1998; Garg, 1998; Kaur *et al.*, 2002).

Garg (1998) monitored changes in an alkali soil under four tree species, which included acacia [*A. nilotica* (L.) Willd. ex Delile], shisham [*D. sissoo* Roxb. ex DC.], mesquite [*P. juliflora* (Sw.) DC.], and arjuna [*T. arjuna* Bedd.]. Shisham and mesquite were more efficient in terms of biomass production and decreasing Na^+ levels in the soil. Similarly, there was greater microbial activity in upper 0.6 m soil under these species due to the accumulation of humus from the decomposition of leaf litter and root decay, which increased soil organic C. The rate of increase was low for the first 2–4 years, exponential between 4 and 6 years, and plateau at a low rate for 6–8 years. Bhojvaid and Timmer (1998) reported that establishment of mesquite on a sodic field increased organic C of the top 1.2 m soil from 11.8 to 13.3 Mg C ha^{-1} in 5 years, 34.2 Mg C ha^{-1} in 7 years, and 54.3 Mg C ha^{-1} in 30 years. The average annual rate of increase in soil organic C was 1.4 Mg ha^{-1} over the 30-year period. Other estimates from field studies on alkali soils suggest that various land-use systems consisting of a number of grasses and trees can sequester organic C in the range of 0.2–0.8 Mg C ha^{-1} $year^{-1}$ (Table 12).

Soils in arid and semiarid areas generally contain the largest pools of inorganic C, which consist of two components: (1) primary inorganic carbonates or lithogenic inorganic carbonates, and (2) secondary inorganic carbonates also known as pedogenic inorganic carbonates (Lal, 2002). Secondary carbonates are formed through the dissolution of primary carbonates and from the reprecipitation of weathering products. The reaction of CO_2 with H_2O and Ca^{2+} and Mg^{2+} in the upper soil horizon, followed by the leaching of the products into the subsoil and their subsequent reprecipitation results in the formation of secondary carbonates and in the sequestration of CO_2 (Sahrawat, 2003). Therefore, the leaching of HCO_3^- through the soil profile, especially by irrigation management, could be a significant pathway leading to sequestration of soil inorganic C. Moreover, inorganic form of C is converted to organic form by plants through photosynthesis, and in soils through the reaction of CO_3^{2-} with decomposing organic matter (added via phytoremediation). In soil, inorganic C gets dissolved through the actions of acidic root exudates and H_2CO_3 formed by the reaction with CO_2 resulting from root respiration in aqueous medium. Thus, the transfer of C from inorganic to organic form provides a better environment for C sequestration, soil conservation, and environmental quality (Bhattacharyya *et al.*, 2004; Sahrawat *et al.*, 2005). The rate at which C is sequestered through this pathway may range between 0.25 and 1.0 Mg C ha^{-1} $year^{-1}$ (Wilding, 1999). When phytoremediation is used to ameliorate sodic soils and HCO_3^- is leached as a by-product of the overall reaction, the amelioration process could sequester

Table 12 Potential of two land-use systems (grass only and tree-grass) for carbon (C) sequestration in a calcareous alkali soil (pH = 10.0–10.2; EC = 2.0–6.4 dS m^{-1}) (calculated from the data reported by Kaur *et al.*, 2002)

Treatment[a]	Organic C in soil (g kg^{-1}) at different depths[b] 0–0.075 m	0.075–0.15 m	Mean	C sequestration (Mg ha^{-1} $year^{-1}$)[c]
Desmostachya	2.9	1.6	2.3	0.33
Sporobolus	2.4	1.3	1.8	0.17
Acacia + *Desmostachya*	3.6	1.8	2.7	0.47
Dalbergia + *Desmostachya*	4.6	2.4	3.5	0.73
Prosopis + *Desmostachya*	4.7	2.5	3.6	0.77
Acacia + *Desmostachya*	2.6	1.4	2.0	0.23
Dalbergia + *Desmostachya*	3.2	1.7	2.5	0.40
Prosopis + *Desmostachya*	3.6	1.9	2.8	0.50

[a] *Desmostachya* [*Desmostachya bipinnata* (L.) Stapf.], *Sporobolus* (*Sporobolus marginatus* Hochst. ex A. Rich), *Acacia* [*Acacia nilotica* (L.) Willd. ex Delile], *Dalbergia* (*Dalbergia sissoo* Roxb. ex DC.), *Prosopis* [*Prosopis juliflora* (Sw.) DC.].
[b] After 6 years of plantation.
[c] Assuming initial C content in the soil as 1.3 g kg^{-1} (average of the C content, which ranged from 1.0 to 1.6 g kg^{-1}) and mass of 0.15 m depth of 1 ha as 2×10^6 kg, the rate of organic C sequestration in the soil under each treatment was calculated as: Organic C sequestration (Mg ha^{-1} $year^{-1}$) = [(mean C content − original C content in soil) 2]/6.

soil inorganic C (Lal, 2001; Sahrawat, 2003). Thus, phytoremediation could lead to both organic and inorganic C sequestration simultaneously.

The plant material added to sodic or saline-sodic soils as a part of the phytoremediation process leads to organic C sequestration, and the rate of which depends on several soil and environmental factors. Among the soil factors, texture and mineralogy are more important. Among the environmental factors, moisture regime and temperature control decomposition of organic matter added and the residence time of C in the soil. In addition, the amount, and more importantly, the quality of organic matter added via plant shoots and roots have an overwhelming effect on soil organic C turnover and storage in the soil profile. Also, the plant species used for phytoremediation have a wide range in their decomposition and turnover rates, and C storage in the soil (Kiem and Koegel-Knabner, 2003; Oades, 1988; Sahrawat, 2004; Sariyildiz and Anderson, 2003; Six *et al.*, 2002; Torn *et al.*, 1997). As discussed earlier in this section, fresh organic matter added to the soil influences C sequestration via soil inorganic C (Sahrawat, 2003; Sahrawat *et al.*, 2005). However, no documented evidence exists that quantifies the effect of different sodic soil amelioration methods on inorganic C sequestration. With growing interest in C sequestration, the degraded soils in the arid and semiarid regions are expected to play a crucial role in stabilizing the atmospheric concentration of CO_2 by employing means that are in line with the sustainable agricultural practices (César Izzaurralde *et al.*, 2001).

4.4. Plant species for phytoremediation

An appropriate selection of plant species capable of producing adequate biomass is vital during phytoremediation. Such selection is generally based on the ability of the species to withstand elevated levels of soil salinity (Maas and Hoffman, 1977) and sodicity (Gupta and Abrol, 1990) while also providing a saleable product or one that can be used on-farm (Qadir and Oster, 2002). The salt resistance of a crop is not an exact value because it depends on several soil, crop, and climatic factors. It reflects the capability of a crop to endure the effects of excess root zone salinity. Considerable variation exists among crops to resist ambient levels of salinity (Table 13) and sodicity (Table 14). Such inter- and intracrop diversity can be exploited to identify local crops that are better adaptable to saline-sodic soil conditions (Maas and Grattan, 1999; Shannon, 1997).

Maas and Hoffman (1977) proposed a linear response function model to characterize crops regarding their salt resistances. Two parameters obtained from this model are: (1) the threshold soil salinity (the maximum allowable soil salinity for a crop without yield reduction), and (2) the slope (the percentage yield decrease per unit increase in salinity beyond the threshold salinity level). The data, presented in terms of EC_e at 25 °C, serve only as a guideline to relative capabilities of the crops to withstand salinity. The threshold salinity levels and slope values obtained from Maas–Hoffman equation can be used to calculate relative yield (Y_r) for any given soil salinity exceeding the threshold level by using Eq. (10):

$$Y_r = 100 - b(\mathrm{EC_e} - \mathrm{EC_{th}}) \qquad (10)$$

where EC_{th} is threshold saturated paste extractable salinity level expressed in dS m^{-1}, b is slope expressed in percentage per dS m^{-1}, and EC_e is average electrical conductivity of the saturated soil paste extract of the root zone expressed as dS m^{-1}.

The two-piece linear response function (Maas and Hoffman, 1977) is also reasonably accurate when salinity is expressed in terms of osmotic potential of the soil solution at field capacity. In cases where the osmotic potential of the soil solution is known, the crop yield response can be determined as a function of the osmotic stress that the plants experience (Maas and Grattan, 1999).

Crops used as phytoremediation tool for saline-sodic soils may also experience oxygen deficiency. This can be expected for three reasons: (1) the need to overirrigate in providing the needed leaching to control salinity levels in the

Table 13 Yield potentials of some grain, forage, vegetable, and fiber crops as a function of average root zone salinity[a]

Crop		Average root zone salinity (dS m^{-1}) at specified yield potentials		
Common name	Botanical name	50%	80%	100%
Triticale (grain)	× *Triticosecale*	26	14	6
Kallar grass[b]	*Leptochloa fusca* (L.) Kunth	22	14	9
Durum wheat	*Triticum durum* Desf.	19	11	6
Tall wheat grass	*Agropyron elongatum* (Host) Beauv.	19	12	8
Barley	*Hordeum vulgare* L.	18	12	8
Cotton	*Gossypium hirsutum* L.	17	12	8
Rye	*Secale cereale* L.	16	13	11
Sugar beet	*Beta vulgaris* L.	16	10	7
Bermuda grass	*Cynodon dactylon* (L.) Pers.	15	10	7
Sudan grass	*Sorghum sudanese* (Piper) Stapf.	14	8	3
Sesbania	*Sesbania bispinosa* (Jacq.) W. Wight	13	9	6
Wheat	*Triticum aestivum* L.	13	9	6
Purslane	*Portulaca oleracea* L.	11	8	6
Sorghum	*Sorghum bicolor* (L.) Moench	10	8	7
Alfalfa	*Medicago sativa* L.	9	5	2
Spinach	*Spinacia oleracea* L.	9	5	2
Broccoli	*Brassica oleracea* L. (Botrytis Group)	8	5	3
Rice	*Oryza sativa* L.	7	5	3
Potato	*Solanum tuberosum* L.	7	4	2
Maize	*Zea mays* L.	6	3	2

[a] Based on the salt tolerance data of respective crops and percentage decrease in yield per unit increase in root zone salinity in terms of dS m^{-1} (Calculated from the data reported by Maas and Grattan, 1999). These data serve only as a guideline to relative resistances among crops. Absolute resistances vary and depend on climate, soil conditions, and cultural practices.

[b] Yield potential calculated from Malik *et al.* (1986).

soil, (2) the likelihood that problem soils—excessively saline and sodic with low infiltration rates and hydraulic conductivities—will be selected in the first place, and (3) inundation (surface ponding) due to a prolonged rainy season. Root zone salinity and sodicity in conjunction with oxygen deficiency affect active transport and exclusion processes in root cell membranes compared with saline nonwaterlogged conditions (Drew, 1983). The genotypes showing greater resistance against the combined effects of salinity, sodicity, and hypoxia would be a better choice for the phytoremediation approach.

Table 14 Ranges of ESP in soils indicating about 50% of the potential yields of different crops (based on the data reported by Gupta and Abrol, 1990)

	Crop	
ESP range	Common name	Botanical name
10–15	Safflower	*Carthamus tinctorius* L.
	Mash	*Vigna mungo* (L.) Hepper
	Pea	*Pisum sativum* L.
	Lentil	*Lens culinaris* Medik.
	Pigeon pea	*Cajanus cajan* (L.) Millsp.
	Urd-bean	*Phaseolus mungo* L.
16–20	Bengal gram	*Cicer arietinum* L.
	Soybean	*Glycine max* (L.) Merr.
20–25	Groundnut	*Apios americana* Medik.
	Cowpea	*Vigna unguiculata* (L.) Walp.
	Onion	*Allium cepa* L.
	Pearl millet	*Pennisetum glaucum* (L.) R. Br.
25–30	Linseed	*Linum usitatissimum* L.
	Garlic	*Allium sativum* L.
	Guar	*Cyamopsis tetragonoloba* (L.) Taub.
30–50	Indian mustard	*Brassica juncea* (L.) Czern.
	Wheat	*Triticum aestivum* L.
	Sunflower	*Helianthus annuus* L.
	Guinea grass	*Panicum maximum* Jacq.
50–60	Barley	*Hordeum vulgare* L.
	Sesbania	*Sesbania bispinosa* (Jacq.) W. Wight
60–70	Rice	*Oryza sativa* L.
	Para grass	*Brachiaria mutica* (Forssk.) Stapf.
70+	Bermuda grass	*Cynodon dactylon* (L.) Pers
	Kallar/Karnal grass	*Leptochloa fusca* (L.) Kunth
	Rhodes grass	*Chloris gayana* Kunth

Several crops, shrubs, trees, and grasses have been used during phytoremediation of sodic and saline-sodic soils. Some successful examples are Kallar grass (Kumar and Abrol, 1984; Malik *et al.*, 1986), sesbania (Ahmad *et al.*, 1990; Qadir *et al.*, 2002), alfalfa (Ilyas *et al.*, 1993), Bermuda grass (Kelley, 1937; Oster *et al.*, 1999), or sordan (Robbins, 1986a). Several other plant species have produced adequate biomass on salt-affected soils. These include shrub species from the genera *Atriplex* and *Maireana* (Barrett-Lennard, 2002; Malcolm, 1993), *Kochia scoparia* L. (Garduno, 1993), *Salicornia bigelovii* Torr. (Glenn *et al.*, 1996), *E. crusgalli* (L.) P. Beauv. (Aslam *et al.*, 1987), *Portulaca oleracea* L. (Grieve and Suarez, 1997), and *Glycyrrhiza glabra* L. (Kushiev *et al.*, 2005), among others. However, it is imperative to compare them with other species already tested for sodic soil amelioration. In addition, efforts are needed to assess other crops such as high-value medicinal and aromatic species that could have the potential for adequate growth on sodic and saline-sodic soils.

A number of tree plantations have been grown on sodic and saline-sodic soils. These include: *T. arjuna* (Roxb. ex DC.) Wight & Arn. (Jain and Singh, 1998), *P. juliflora* (Sw.) DC. (Bhojvaid and Timmer, 1998), *D. sissoo* Roxb. ex DC., *A. nilotica* (L.) Willd. ex Delile (Kaur *et al.*, 2002), *Parkinsonia aculeata* L. and *P. cineraria* (L.) Druce (Qureshi and Barrett-Lennard, 1998), *Sesbania sesban* (L.) Merr. and *Tamarix dioica* Roxb. ex Roth. (Singh, 1989), and *Leucaena leucocephala* (Lam.) de Wit (Qureshi *et al.*, 1993), among others. In Australia, Farrington and Salama (1996) recommended revegetation by trees to be the best long-term option for controlling dryland salinity. Qureshi and Barrett-Lennard (1998) have provided useful information regarding sources of seeds, nursery raising techniques, and land preparation and planting procedures for 18 different tree and shrub species having potential for growth on salt-affected soils.

Any change in a cropping pattern or farm operation is driven by the cost of inputs involved and the subsequent economic benefits. Several studies have compared the economics of sodic soil amelioration. Singh and Singh (1989) found a net loss (cost:benefit 1.00:0.75) during phytoremediation although the growth of Karnal grass was adequate, which helped reduce soil sodicity. They attributed this economic loss to the small market demand of the grass in the presence of other good-quality forages in that locality. On the other hand, the phytoremediation strategy has been found economically beneficial when there was a market demand or local utilization of the crops at the farm level (Chaudhry and Abaidullah, 1988; Sandhu and Qureshi, 1986). Qureshi *et al.* (1993) found agroforestry systems comprising several tree species to be economically viable because of a need for firewood in local markets and effectiveness in amelioration of calcareous saline-sodic soils. On the other hand, the market for firewood is not sufficient to make agroforestry economically viable in California (Oster *et al.*, 1999). Preliminary assessments in Australia suggest that there are 26 salt-resistant plant species capable of producing 13 products (or services) of value to agriculture (Barrett-Lennard, 2002). From an economic perspective much depends on local needs. In an immediate sense, phytoremediation can only be economically beneficial if the selected crops, grasses, or trees have a market demand or local utilization at the farm level. In the long run, one must also consider the value of the improved soils.

5. Perspectives

Recent trends and future projections suggest that the need to produce more food, feed, energy, and fiber for the world's expanding population and changing lifestyles and preferences, will lead to an increase in the use of salt-prone land and water resources (Qadir *et al.*, 2007). This is particularly relevant to less-developed, arid and semiarid countries in which the problems of salinity- and sodicity-induced soil degradation are common. Such widespread occurrence of sodic and saline-sodic soils reveals the need for concerted efforts to rehabilitate these soils in order to enhance their productivity.

A comparable performance of phytoremediation with that of chemical amelioration highlights the effective role of cropping in the amelioration of calcareous sodic and saline-sodic soils. Phytoremediation has shown to be advantageous in several aspects: (1) no financial outlay to purchase chemical amendments, (2) accrued financial or other benefits from crops grown during amelioration, (3) promotion of soil-aggregate stability and creation of macropores that improve soil hydraulic properties and root proliferation, (4) greater plant nutrient availability in soil after phytoremediation, (5) more uniform and greater zone of amelioration in terms of soil depth, and (6) environment consideration in terms of C sequestration in the postamelioration soil. Phytoremediation is effective when used on moderately saline-sodic and sodic soils. However, it does have disadvantages in that it reduces sodicity more slowly than chemical approaches and requires calcite to be present in the soil (although this is commonly found in most sodic soils). In addition, the feasibility of phytoremediation is limited when soil is highly sodic, as this is likely to result in the phytoremediation crop's growth being variable and patchy. Under these conditions, the use of chemical amendments such as gypsum is inevitable.

The process of Na^+ removal from calcareous sodic and saline-sodic soils during phytoremediation has been found to be dominated by P_{CO_2} within the root zone. Large differences in root zone P_{CO_2} values of the crops used in phytoremediation have been observed. The P_{CO_2} and hence soil amelioration efficiency have been found to be directly proportional to crop biomass, root activity, and rate of crop growth. In addition, excess irrigation during peak growth stages would significantly increase the retention of CO_2 through entrapment thereby enhancing the rate of calcite dissolution during phytoremediation. The identification of P_{CO_2} as the single largest driving force for sodic soil amelioration suggests the need to identify crops and crop management practices that enhance CO_2 production within the root zone to ameliorate sodic soils more efficiently, especially in areas where chemical amendments are not available or are too expensive. Furthermore, it is evident from studies quantifying processes contributing to accelerated soil acidification under cropping systems that they could be effectively used to enhance H^+ generation under sodic conditions. In this respect, plant species with high ash alkalinity, large aboveground biomass production, and the promotion of highly exploitive production systems that rely on N_2-fixing species and encompass net biomass export would maximize H^+ addition rates. Such a system could be typically of a cut-and-carry forage crop production that includes a N_2-fixing legume component. The removal of Na^+ by crop harvest has a minor contribution to amelioration of sodic and saline-sodic soils.

Degradation of soil resources and desertification of drylands has led to the depletion of soil organic C, decline in biomass production, contamination of water resources, and emission of greenhouse gases such as CO_2 at an accelerated rate. Such trends will intensify in the foreseeable future if due attention is not given to reverse the resource degradation. Amelioration of sodic and saline-sodic soils vis-à-vis C sequestration hold promise to reverse the resource degradation processes. However, to achieve such objectives socially acceptable and economically attractive policies are needed for the implementation of technically sound practices on a long-term basis that should also involve provision for monitoring the actual amount of C sequestration.

Soil management under different levels of salinity and sodicity will continue to be a challenge for researchers, farm advisors, and farmers. Crop-based sodic soil management built on the accumulated wisdom of stakeholders will not only enhance farmers' participation but will also assist them in the adoption of pertinent measures, as these need to be adopted at the community level. Such participatory approaches will ensure that the views and ideas of the local population are taken into account, and may create a sense of ownership among the members of the farming community. Community-based sodic soil management would help to strengthen linkages among researchers, farm advisors, and farmers. These linkages will continue to be fostered as the use of sodic soils becomes more prevalent. The successful amelioration of these soils through phytoremediation will require a greater understanding of the potential of phytoremediation species to withstand ambient salinity and sodicity levels in soil and water, and also of the uses and markets for the agricultural products produced.

Considering the challenges associated with sodic soil management and environmental conservation, we believe that the time has come to consider such soils a useful resource of economic value rather than an environmental burden. The use of sodic soils should therefore be considered to be an opportunity to shift from subsistence farming to progressive and income-generating farming. Clearly, phytoremediation is an effective low-cost intervention for the amelioration of these soils that is a viable solution for resource-poor farmers. This approach has the potential for large-scale adoption under government- or community-based programs aimed at the amelioration and improved productivity of degraded common property resources. We believe that the information provided herein will stimulate strategic research for further elucidation of the role of phytoremediation in the restoration of sodic and sodic-saline soils for sustainable agriculture and conservation of environmental quality.

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