Phytoremediation of Sodic and Saline-Sodic Soils

M. Qadir[1], A.D. Noble[2], S. Schubert[3] and A. Ghafoor[4]
[1]*International Center for Agricultural Research in the Dry Areas (ICARDA), P.O. Box 5466, Aleppo, Syria (E-mail: M.Qadir@cgiar.org)*
[2]*International Water Management Institute (IWMI), Kasetsart University, Bangkok, Thailand*
[3]*Institute of Plant Nutrition, Justus Liebig University, 35392 Giessen, Germany*
[4]*Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan*

1 INTRODUCTION

Sodic and saline-sodic soils are characterized by the occurrence of sodium (Na^+) at levels that cause poor physical properties and fertility problems, threatening agricultural productivity in many arid and semi-arid regions. Amelioration of these soils is driven by providing a soluble source of calcium (Ca^{2+}) to replace excess Na^+ on the cation exchange complex. The displaced Na^+ is leached from the root zone, a process that requires soil permeability and provision of natural or artificial drainage. Many sodic soils, however, contain inherent or precipitated sources of Ca^{2+}, i.e. calcite ($CaCO_3$) at varying depths within the soil profile. Owing to the negligible solubility of calcite (0.14 mmol L^{-1}), its natural dissolution does not provide sufficient Ca^{2+} to ameliorate these soils. Consequently, attempts have been made to ameliorate sodic soils by the application of chemical amendments. Some amendments supply soluble Ca^{2+} to the soil to replace exchangeable Na^+, while others assist in increasing the dissolution rate of calcite. The costs of these products have increased over the past two decades due to competing demands from industry and reductions in government subsidies for their agricultural use in many developing countries. Consequently, chemical amelioration has become prohibitively expensive for financially disadvantaged farmers. Research along with farmer knowledge has revealed that these soils can be brought back to a highly productive state by phytoremediation—a plant-assisted amelioration approach—that does not use chemical amendments (Robbins, 1986a; Qadir & Oster, 2002). Synonyms for phytoremediation include vegetative bioremediation and biological reclamation.

Typical plant-assisted amelioration strategies for contaminated soils, such as those containing elevated levels of heavy metals and metalloids, work by growing specific plant species capable of hyper-accumulation of target ionic species in their shoots, thereby removing them from the soil (McGrath et al., 2002). In contrast, phytoremediation of sodic soils is achieved by the ability of plant roots to increase the dissolution rate of calcite, providing enhanced levels of Ca^{2+} in soil solution. The salinity-sodicity combination present in the soil solution during phytoremediation maintains adequate soil structure and aggregate stability that enhances the amelioration process (Qadir and Oster, 2002). This paper highlights the role of crops and different driving forces for phytoremediation of sodic soils. This information will assist in choosing appropriate crops and management practices to achieve maximum benefit during the amelioration process.

2 DRIVING FORCES FOR PHYTOREMEDIATION OF SODIC SOILS

Phytoremediation of calcareous sodic and saline-sodic soils (*Phyto*$_{Sodic}$) is a promising option to increase the dissolution rate of calcite through processes at the soil-root interface resulting in enhanced levels of Ca^{2+} in soil solution. It is a function of the following factors:

$$Phyto_{\mathrm{Sodic}} = \Sigma R_{P_{CO_2}} + R_{H^+} + R_{\mathrm{Phy}} + S_{Na^+} \quad [1]$$

where $R_{P_{CO_2}}$ refers to increased partial pressure of CO_2 within the root zone; R_{H^+} is enhanced H^+ release in the root zone in the case of certain N_2-fixing crops; R_{Phy} deals with physical effects of roots in improving soil aggregation and hydraulic properties of the root zone;, and S_{Na^+} consists of Na^+ content of shoots which is removed through harvest of aerial plant portion. The collective effects of these factors ultimately lead to soil amelioration.

The enhanced level of P_{CO_2} in the root zone during cropping is a major mechanism for phytoremediation of calcareous sodic soils (Table 1). In soils, P_{CO_2} is normally in the range of 1 kPa, and increases dramatically under anaerobic and cropped conditions (Robbins, 1986b). The P_{CO_2} effect in calcareous sodic soils under cropping may be expressed through a series of processes: (1) an increase in soil atmosphere CO_2 concentration; (2) dissolution of CO_2 in water to form carbonic acid (H_2CO_3); (3) dissociation of H_2CO_3 to form proton (H^+) and bicarbonate (HCO_3^-); (4) reaction of H^+ with calcite to produce Ca^{2+}; (5) displacement of exchangeable Na^+ by Ca^{2+} as a result of increased Ca^{2+} in soil solution; (6) leaching of the displaced Na^+ in percolating water; and (7) subsequent reduction in soil sodicity.

Table 1 Net Na^+ removal (± standard error) from a calcareous sodic soil (pH_s = 8.6, EC_e = 2.4 dS m^{-1}, ESP = 33) in different cropped and non-cropped treatments as a function of partial pressure of CO_2 (P_{CO_2}) in a lysimeter study (modified from Robbins, 1986a & 1986b)

Treatment	P_{CO_2} range (kPa)	Na^+ removal (mol)
Control (without crop or chemical amendment application)	0.9-4.3	1.0±0.1
Gypsum applied at 5 kg m^{-2} soil and incorporated in 0-0.2 m	0.9-2.4	3.3±0.3
Manure applied at 5 kg m^{-2} soil and incorporated in 0-0.2 m	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

There are many mechanisms other than root respiration that affect P_{CO_2} levels in soils. These include (1) production of CO_2 from the oxidation of root exudates by soil organisms that metabolize polysaccharides, proteins, and peptides to produce CO_2; and (2) the production of organic acids by soil organisms and organic acid dissolution of calcite. Whether the source of CO_2 is 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 ambient P_{CO_2}.

In addition to aqueous CO_2 that ultimately results in the formation of H^+ and HCO_3^-, another source of H^+ in the rhizosphere is generated through the cropping of N_2-fixing legumes (Schubert & Yan, 1997). The release of H^+ from plant roots contributes to a decrease in pH in non-calcareous soils. However, the pH of calcareous soils does not decrease to a greater extent as the H^+ produced are neutralized by the dissolution of calcite. Qadir et al. (2003) found that H^+ release by N_2-fixing crops increases the rate of Na^+ removal from calcareous sodic soils. In a lysimeter study, they evaluated N_2-fixing alfalfa (*Medicago sativa* L.) against NH_4NO_3-fed alfalfa to ameliorate a calcareous sodic soil (pH_s = 7.4, EC_e = 3.1 dS m^{-1}, ESP = 27.6). Despite the fact that both cropped treatments produced statistically similar root and shoot biomass, there was 8% greater removal of Na^+ in leachates collected from the lysimeters grown with N_2-fixing alfalfa.

Crop roots can stimulate changes in physical properties of the root zone in several different ways such as removing entrapped air from larger conducting pores, generating alternate wetting and drying cycles, and creating macropores. Aggregate stability is enhanced because of *in situ* production of polysaccharides and fungal hyphae in conjunction with differential dewatering at the root-soil interface. This is consistent with the observation that deep-rooted perennial grasses and legumes can improve root penetration in soil. For example (Ilyas et al., 1993), deep-rooted alfalfa grown for 1 year on a saline-sodic field (pH_s = 8.8, EC_e = 5.6 dS m^{-1}, SAR = 49) caused a two-fold increase in hydraulic conductivity (K_s) of the upper 0.8 m depth where alfalfa roots penetrated. Other phytoremediation treatment—sesbania [*Sesbania bispinosa* (Linn.) W.F. Wight]-wheat (*Triticum aestivum* L.)-sesbania rotation—caused similar increase in K_s up to 0.4 m depth where sesbania roots penetrated.

Harvest of the aerial plant portion of phytoremediation crops removes salts and Na^+ from sodic soils. However, when considering phytoremediation of sodic soils where irrigation is necessary to enhance calcite dissolution and leach Na^+ from the root zone, the contribution of typical salt accumulators through shoot harvest is minimal. This is because besides initial soil salinity and sodicity, salts and Na^+ are added to these soils during irrigation, particularly where irrigation waters are already saline. For example, Kallar grass [*Leptochloa fusca* (L.) Kunth] is an important phytoremediation crop for calcareous sodic soils. Its above-ground vegetation contains salt in the range of 40 to 80 g kg^{-1} when grown at different levels of salts in the soil. Considering annual forage production of the grass of about 25 Mg ha^{-1}, the volume of irrigation water required to grow the grass is around 10 ML. If irrigation water has EC of 1.5 dS m^{-1}, typical of most waters used to irrigate the grass, the salt content of forage removed from the field would range from 1 to 2 Mg ha^{-1}. In contrast, the amount of salt added via 10 ML irrigation would be 9.6 Mg ha^{-1}. Therefore, the principal method of decreasing soil salinity and sodicity through phytoremediation is through the leaching of salts and Na^+ from the root zone to deeper soil depths rather than removal by above-ground biomass harvesting.

3 COMPARATIVE EFFICINCY OF PHYTOREMEDIATION OF SODIC SOILS

Several plant species of agricultural significance have been effectively used to ameliorate sodic and saline-sodic soils. However, there are considerable differences among the species in their efficiency (Qadir & Oster, 2002). In general, species with greater biomass production as well as tolerance to soil salinity and sodicity and periodic inundation have been found to be suitable for amelioration. In most studies, phytoremediation has shown comparable performance against the conventional chemical approach. However, in some studies phytoremediation was less efficient than chemical treatment because (1) the initial phytoremediation crop in the rotation was not tolerant of ambient soil salinity and sodicity levels; (2) the period of phytoremediation was insufficient to effect remediation, i.e. the crop was grown for one season ($\leq$ 6 months) only; (3) phytoremediation crop was grown during the time, which was not the most suitable growing season; and/or (4) leaching was restricted because insufficient irrigation water was used to displace excess salts and Na^+ below the root zone. In general, phytoremediation worked well on moderately sodic soils provided (1) irrigation was done in excess of crop water requirement to provide adequate leaching, and (2) excess irrigation was applied when the crop growth and hence P_{CO_2} were at their peak. On such soils, phytoremediation was as efficient as chemical amelioration. On highly sodic and saline-sodic soils, chemical treatment superceded the cropped treatment(s).

In most comparative studies, amelioration in gypsum treatments occurred primarily in the zone where the amendment was incorporated. Gypsum in these experiments was mixed into the soil surface, and in most cases, it was agricultural grade and incorporated into upper 0.15 m of the soil. It was only when amelioration approached completion in the zone of incorporation that it began in move to deeper depths. This was a direct effect on the exchange selectivity of cation exchange sites for Ca^{2+} compared to Na^+ in the zone of gypsum application (Suarez, 2001). In phytoremediation treatments, however, amelioration occurred throughout the root zone. This observation was common in sodic soils grown with a range of crops. However, different crops caused a variable degree and depth of soil amelioration, which was influenced by the morphology and volume of root and depth of root penetration.

In addition to amelioration effect, cultivation of appropriate plant species on sodic soils has the potential to mitigate accelerated greenhouse effects by increasing soil carbon (C) contents through biomass production. Bhojvaid & Timmer (1998) reported that establishing mesquite [*Prosopis juliflora* (Swartz) DC] on a sodic field increased organic C in the top 1.2 m soil from 11.8 Mg C ha^{-1} 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 (Kaur et al., 2002) suggest that different land-use systems consisting of a number of grasses and trees on sodic soils can sequester organic C in the range of 0.2 to 0.8 Mg C ha^{-1} yr^{-1}.

4 CONCLUSIONS

Phytoremediation of sodic and saline-sodic soils is an effective low-cost intervention for resource-poor farmers. The advantages of this approach are: (1) no investment to purchase chemical amendments is required; (2) there are accrued financial or other benefits from crops grown during amelioration; (3) soil aggregate stability and porosity are increased as a result of root activity with subsequent improvement in soil hydraulic properties; (4) plant nutrient availability in the soil is improved because of organic matter addition by below-ground plant material as well as N fixation when leguminous crops are used; (5) the zone of amelioration is more uniform and deeper, particularly in case of deep-rooted crops; and (6) C sequestration is achieved in the post-amelioration soil.

This plant-assisted amelioration strategy is a promising option to increase the dissolution rate of calcite through processes at the soil-root interface, thereby resulting in enhanced levels of Ca^{2+} in the soil solution. A key area of research will be the identification of plant species that can withstand high levels of salts and Na^+ and have a propensity to produce large quantities CO_2 and H^+ in the root zone, coupled with high ash alkalinity. Production systems that maximize biomass export will also be beneficial.

5 REFERENCES

Bhojvaid, P.P. & Timmer, V. 1998. Soil dynamics in an age sequence of *Prosopis juliflora* planted for sodic soil restoration in India. *Forest Ecology and Management* 106: 181-193.

Ilyas, M. Miller, R.W. & Qureshi, R.H. 1993. Hydraulic conductivity of saline-sodic soil after gypsum application and cropping. *Soil Science Society of America Journal* 57: 1580-1585.

Kaur, B. Gupta, S.R. & Singh, G. 2002. Bioamelioration of a sodic soil by silvopastoral systems in northwestern India. *Agroforestry Systems* 54: 13-20.

McGrath, S.P. Zhao, F.J. & Lombi, E. 2002. Phytoremediation of metals, metalloids, and radionuclides. *Advances in Agronomy* 75: 1-56.

Qadir, M. & Oster, J.D. 2002. Vegetative bioremediation of calcareous sodic soils: History, mechanisms, and evaluation. *Irrigation Science* 21: 91-101.

Qadir, M. Steffens, D. Yan, F. & Schubert, S. 2003. Proton release by N_2-fixing plant roots: a possible contribution to phytoremediation of calcareous sodic soils. *Journal of Plant Nutrition and Soil Science* 166: 14-22.

Robbins, C.W. 1986a. Sodic calcareous soil reclamation as affected by different amendments and crops. *Agronomy Journal* 78: 916-920.

Robbins, C.W. 1986b. Carbon dioxide partial pressure in lysimeter soils. *Agronomy Journal* 78: 151-158.

Schubert, S. & Yan, F. 1997. Nitrate and ammonium nutrition of plants: effects on acid/base balance and adaptation of root cell plasmalemma H^+ ATPase. *Journal of Plant Nutrition and Soil Science* 160: 275-281.

Suarez, D.L. 2001. Sodic soil reclamation: modelling and field study. *Australian Journal of Soil Research* 39: 1225-1246.