Biosaline Agriculture and Salinity Tolerance in Plants

Edited by Münir Öztürk, Yoav Waisel, M. Ajmal Khan and Güven Görk

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Vegetative bioremediation of sodic and saline-sodic soils for productivity enhancement and environment conservation

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Introduction

Salt-affected soils occupy nearly 20% of irrigated area worldwide [1]. As a major category ofsalt-affected soils, sodic and saline-sodic soils are characterized by the occurrence of sodium (Na^+) at levels that result in poor physical properties and fertility problems, thereby 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 **[2].** The displaced Na^+ is either leached from the root zone by excess irrigation, aprocess that requires soil permeability and provision of a natural or artificial drainage system, or is taken up by crops.

Many sodic and saline-sodic soils contain inherent or precipitated sources of Ca^{2+}, i.e., calcite ($CaCO_3$) at varying depths. Due to its negligible solubility (0.14 mmol L^{-1}), natural dissolution of calcite does not provide sufficient Ca^{2+} to ameliorate these soils. Consequently, amelioration of these soils has been dominated by the application of chemical amendments **[3].** Some amendments supply soluble sources of Ca^{2+} to the soil solution, which then replace excess Na+ on the exchange complex, while others assist in increasing the dissolution rate of calcite. There have been constraints with chemical amelioration in several developing countries during the last two decades because of 1) low-quality of amendments containing a large fraction of impurities, 2) restricted availability of amendments when needed for amelioration, and/or 3) increased costs of amendments due to competing demands by industry and reductions in government subsidies for their agricultural use. Owing to oveniding importanceof the last factor, chemical amelioration bas become prohibitively expensive for resource-poorfanners. However, there is growing evidence from researchers and farmers indicatingthat these soils can be brought back to a highly productive state using a plant-assisted amelioration approach – vegetative bioremediation – that does not rely on chemical amendments [4-6]. Synonymous terms for vegetative bioremediation include phytomelioration, phytoremediation, and biological reclamation.

Typical plant-assisted amelioration strategies for contaminated soils, such as those containing elevated levels of heavy metals and metalloids, work through cultivation of specific plant species capable of hyper-accumulation of target ionic species in their shoots, thereby removing them from the soil [7]. In contrast, vegetative bioremediation of sodic and saline-scdic 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. The salinity-scdicity combination present in the soil solution during vegetative bioremediation maintains adequate soil structure and aggregate stability that enhance the amelioration process [8]. This chapter highlights the role of cropping for vegetative bioremediation of calcareous sudic and saline-sodic soils and its evaluation against other amelioration approaches. This information will assist researchers and farm advisors in choosing appropriate crops as well as crop, soil and irrigation management practices to achieve maximum benefit during the amelioration process.

Vegetative bioremediation of sodic and saline-sodic soils

Vegetative bioremediation of calcareous sodic and saline-sodic soils is a promising option that increases the dissolution rate of calcite through the processes at the soil-root interface resulting in enhanced levels of Ca^{2+} in soil solution. Vegetative bioremediation (V_{Bio}) is a function of the following factors:

$$V_{Bio} = \sum R_{PCO2} + R_{H+} + R_{Phy} + S_{Na+} \tag{1}$$

where $R_{P_{CO_2}}$ refers to increased partial pressure of CO_2 within the root zone. R_{H+} is enhanced proton (H^+) release in the root zone in 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 shoot which is removed through harvest of aerial plant portion. The collective effects of these factors ultimately lead to soil amelioration, provided leaching and drainage are adequate [Fig. 1).

Comparative efficiency of vegetative bioremediation

The evaluation of vegetative bioremediation and chemical approaches in various countries reveals comparable performance of both in terms of sodic soil amelioration. Results of a field experiment conducted on a barren, calcareous, 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 Kamal grass (Leptochloa *fusca* (L.) Kunth), was comparable with soil application of gypsum at 12.5 Mg ha^{-1} [9]. The yield of first rice (Oryza sativa L.) 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 Kamal grasses, respectively. The corresponding

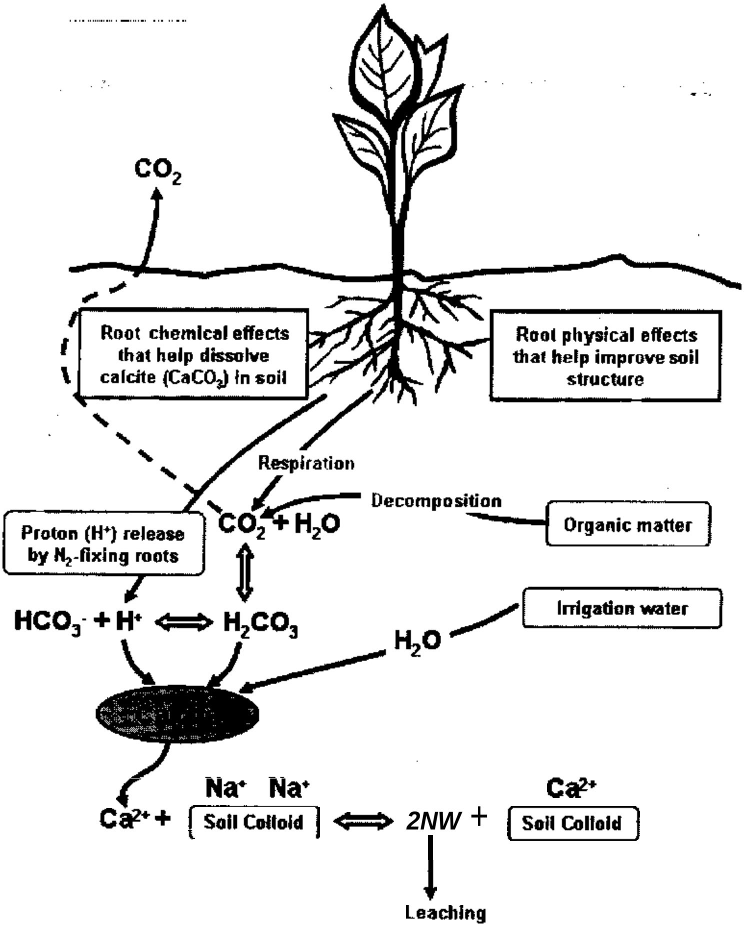

Figure 1. A conceptual model for the chemical reactions involved in calcite ($CaCO_3$) dissolution and amelioration of calcareous sodic and saline-sodic soils during vegetative bioremediation

rice yields after 2 years of grass cropping were 5.3 and 6.1 Mg ha^{-1}. In another field experiment [10], amelioration efficiency of Kallar grass was evaluated during different periods of root decay by leaching a calcareous, silty clay loam, saline-sodic soil (pH, = 8.3-9.3, EC, = 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 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 gypsum-treated soil.

In a field study [11], cropping of seshania (Sesbania bispinosa (Linn.) W.E Wight), Kallar grass, and sordan (Sorghum ***xdrummondii*** (Steud.) Millsp. &Chase) was compared against gypsum application (13 Mg ha^{-1}) on a calcareous, sandy clay loam, saline-sodic soil (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) with average forage yields in the order: sesbania(40.8 Mg ha^{-1}) > Kallar grass (29.3 Mg ha^{-1}) > sordan (24.7 Mg ha^{-1}). After two cropping seasons, the treatment efficiency for grain yield of the subsequent wheat (Triticum aestivum L.) crop was in the order: sesbania (3.79 Mg ha^{-1}) ≈ gypsum (3.68 Mg ha^{-1}) > Kallar grass (3.14 Mg ha^{-1}) > sordan (2.27 Mg ha^{-1}) > control (0.65 Mg ha^{-1}). In a later field experiment [5], four plant species – Kallar grass, sesbania, millet rice, and finger millet – were tested against gypsum application (14.8 Mg ha^{-1}) to ameliorate a calcareous, sandy clay loam, saline-sodic soil (EC_e = 9.1–11.0 dS m^{-1}, SAR = 59.4-72.4). The treatment effectiveness to decrease soil EC_e and SAR was in the order: gypsum ≈ sesbania > Kallar grass > millet rice > finger millet. Forage yields of the plant species were directly proportional to their soil amelioration efficiency.

Some field trials of cmp bioremediation techniques have not been successful primarily because a salt-resistant forage cmp was not the first crop in the rotation. In a field experiment [12], biological (rice-wheat rotation), physical + biological (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 + biological (gypsum at 100% gypsum requirement of the upper 0.15 m of soil + rotation), and chemical + physical + biological (gypsum + subsoiling + rotation) methods were compared 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: gypsum (1.99 Mg ha^{-1}) > gypsum+ subsoiling (1.84 Mg ha^{-1}) > subsoiling (1.41 Mg ha^{-1}) > vegetative bioremediation (1.02 Mg ha^{-1}). Gypsum and gypsum + subsoiling treatments had similar values for the wheat grain yield (2.72 Mg ha^{-1}) followed by subsoiling (1.79 Mg ha^{-1}) and vegetative bioremediation (1.46 Mg ha^{-1}). Within the upper 0.15 m depth, all the treatments decreased EC_e levels less than 5 dS m^{-1} and ESP levels less than 22 on both the soils.

Several crop rotations have been evaluated for the amelioration of saline-sodic and sodic soils. Three imgated crop rotations were tested 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). The rotations distributed in plots of 18 m^2 were: sesbania-barley (Hordeurn vulgare L.), rice-wheat, and Kallar grass-alfalfa (Medicago sativa L.). All the crop rotations reclaimed the upper 0.15 m of soil after 1 year (SAR < 10) as did amelioration by the non-cropped gypsum treatment, which decreased SAR less than 14 [13]. Although initial salinity and sodicity levels of this soil were closer to that used by [12], there were three differences: 1) the soil was relatively coarser in texture, 2) the plots were imgated with canal water (EC = 0.3 dS m^{-1}, SAR = 0.5). and 3) the irrigation water was applied in excess of crop water needs to leach Na^+ to lower depths.

In an evaluation of 14 experiments, carried out in different parts of the world. there was a comparable effect of chemical and bioremediation approaches [14]. The chemical treatment (application of gypsum in all experiments) caused 62% decrease in original sodicity levels, whereas a 52 % decrease was calculated for the vegetative bioremediation treatments. However, in some experiments bioremediation was either unsuccessful or much less efficient than the chemical treatment for the reasons: 1) a crop resistant to ambient soil salinity and sodicity levels was not the first in the crop rotation; 2) bioremediation crop was grown during the time, which was not its most suitable growing season; 3) time was insufficient to exploit the potential impact of the bioremediation 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. bioremediation worked well on moderately sodic and saline-sodic soils, provided 1) irrigation was in excess of crop water requirement to provide adequate leaching; and **2)** the excess imgation was applied when the crop growth and hence P_{CO_2} were at their ***peak.*** On these soils, the performance of vegetative bioremediation was comparable with soil application of gypsum. On highly sodic and saline-sodic soils, chemical treatment was better than the cropped treatments.

Additional benefits of vegetative bioremediation

Nutrient availability status of post-amelioration soil is crucial for the growth of subsequent crops. Research on nutrient behavior during amelioration using chemical and biological methods has been conducted by determining the availability status of some **macro-** and micro-nutrients during amelioration of a calcareous saline-sodic soil (pH, = 8.2-8.6, EC_e = 7.4-9.0 dS m^{-1}, **SAR** = 55.6–73.0). The bioremediation treatments included 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 bioremediation plots resulting from the production of root exudates and likely dissolution of some nutrient-coated calcite. Conversely, the non-cropped gypsum treatment decreased 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 N_2-fixing sesbania treatment where N content was increased from 0.49 g kg^{-1} to 0.53 g kg–'. There was no treatment effect on soil potassium (K) availability since illite, a K-bearing mineral, was dominant in the clay fraction **[15].**

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 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 [16]. This parameter has been studied in few experiments dealing with sodic soil amelioration through chemical and biological means. After using several combinations of chemical and vegetative bioremediation treatments, DHA and microbial biomass carbon (MBC) were determined [17]. The treatments consisted of Kamal 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}) + Kamal 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 post-amelioration soil were greater (118.7 μg triphenylfomazan g^{-1}) in the bioremediation 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 experimental average of 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 [18], a significant increase in **urease** and dehydrogenase activities was found in alkali soils under permanent vegeration such as grasses. Green manuring of an alkali soil with sesbania has also been reported to increase urease and dehydrogenase activities [19].

Sodic and saline-sodic soils have lost a large fraction of their original carbon (C) pool [20]. The magnitude of the loss may range between 10-30 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. In addition to amelioration effect, cultivation of appropriate crops, shrubs, and trees on sodic and saline-sodic soils has the potential to mitigate accelerated greenhouse effects by increasing soil C through biomass production (Tab. 1). Monitoring changes in an alkali soil cropped with four tree species – acacia (Acacia nilotica Willd ex Delile), shisham (Dalbergia sissoo Roxb. ex DC.), mesquite (Prosopis juliflora (Swartz) DC.) and arjuna (Terminalia arjuna Bedd.) – suggested shisham and mesquite as 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 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 *4-6* years, and plateau at a low rate for 6–8 years [21]. Establishment of mesquite on a sodic field increased organic C of the top 1.2 m soil from 118 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 [22]. Other estimates from field studies on alkali soils suggest that different 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} yr^{-1} [6].

Plant species for vegetative bioremediation

The selection of plant species for vegetative bioremediation is generally based on the ability of the species to withstand ambient levels of soil salinity and sodicity while also providing a saleable product or one that can be used on-farm. Considerable variation exists among crops to withstand saline-sodic conditions [23]. Such inter- and intra-crop diversity suggests that field trials be conducted to identify local crops that are adaptable to saline-sodic soil conditions [24]. The fanners, farm advisors, and researchers familiar with local conditions, including crop response to adverse soil conditions and cropping strategies that fit into the local economic conditions, could provide a valuable resource base for making appropriate recommendations. In addition, application of plant breeding approaches is needed to develop crop genotypes with enhanced salt resistance and performance in field conditions [25].

Table 1. 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}). Recalculated from [6]

Treatment[a]	*Organic* C *in* soil (g kg^{-1}) at different depths[b]			**C sequestration** ($Mg\ ha^{-1}\ yr^{-1}$)[c]
	0-0.075 m	0.075–0.15 m	**Mean**	
Desmostachya	2.9	1.6	2.3	0.33
Spombolus	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
Pmsopis + ***Desmostachya***	3.6	1.9	2.8	0.50

'Desmostachya (Desmostachya bipinnata (L.) Stapf), Spombolus (Spombolus marginatus Hochst ex A. Rich), Acacia (Acacia nilotica (L.) Delile), Dalbergia (Dalbergia sissoo Roxb. ex **DC)**, Pmsopis (Pmsopis juliflora (Sw.) DC)
[b]**After** 6 years of plantation
'Assuming initial C content in the soil as 1.3 g kg^{-1} (average of the C content, which ranged from 1.0-1.6 g kg–') 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 sequertr ($Mg\ ha^{-1}\ yr^{-1}$) = [(mean C content -original C content in soil) 2] / 6

Several crops, shrubs, trees, and grasses have been used as vegetative bioremediation tools to ameliorate sodic and saline-sodic soils. Some researchers have favored the inclusion of Kallar grass **[9],** sesbania **[11],** alfalfa **[26],** Bermuda grass [8], or sordan **[4]** as the first cmp to accelerate sodic soil amelioration. Several other plant species have produced adequate biomass on salt-affected soils. These include shrub species from the genera Atriplex and Maireana **[27, 28],** Kochia scoparia **L. [29],** Salicornia bigelovii Torr. **[30],** Echinochloa crusgalli **(L.) P.** Beauv. **[31],** and Portulaca oleracea L. **[32],** among others. However, it is imperative to compare them with other species already tested for sodic soil amelioration. In addition, efforts are needed to search other crops such as high-value medicinal and aromatic species with 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: Terminalia arjuna (Roxb. ex DC.) Wight and Am. **[33],** Pmsopis juliflora (Sw.) DC. ***[22], Dalbergin sissoo Roxb.*** ex DC., Acacia nilotica (L.) Willd. ex Delile **[6],** Parkinsonin aculeata L. and Prosopis cineraria (L.) Druce **[34],** Sesbania sesban (L.) Merr. and Tamarix dioica Roxb. ex Roth **[35],** and Leucaena leucocephala (Lam.) de Wit **[36],** among others. **In** Australia, revegetation by trees was found to be the best long-term option for controlling dryland salinity **[37].** Useful information is available regarding sources of seeds, nursery raising techniques, and land preparation and planting procedures for 18 different tree and shrub species with potential for growth on salt-affected soils **[34].**

Based on cost and benefit analysis, several studies have compared economics of sodic soil amelioration. A net economic loss (cost:benefit 1.00:0.75) was found during vegetative bioremediation although the growth of Kamal grass was adequate, which helped reduce soil sodicity. The economic Loss was attributed to the small market demand of the grass in the presence of other good-quality forages in that locality **[38].** On the other hand, the bioremediation strategy has been found to be economically beneficial when there was a market demand or local utilization of the crops at the farm level **[39, 40].** Agroforestty systems comprising several tree species on saline-sodic soils have been found to be economically feasible in some developing countries because of firewood need in local markets **[36].** On the other hand, the market for firewood is not supportive to make agroforestry economically viable in California **[8].** Preliminary assessments in Australia suggest that there are 26 salt-resistant plant species capable of producing 13 products (or services) of value to agriculture **[27].** From an economic perspective much depends on local needs. In an immediate sense, vegetative bioremediation can only be economically feasible 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.

Conclusions

In recent decades, vegetative bioremediation bas been found to be an efficient, inexpensive, and environmentally acceptable strategy to ameliorate sodic and saline-sodic soils. Its comparable performance with that of chemical amelioration highlights the effective role of cropping in the amelioration of these soils. Vegetative bioremediation 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 macro-pores that improve soil hydraulic properties and root proliferation, 4) greater plant-nutrient availability in soil after vegetative hioremediation, 5) more uniform and greater zone of amelioration in terms of soil depth, 6) sequestration of C in post-amelioration soil, and 7) environmentally feasible and productive use of otherwise marginal and degraded soils. However, vegetative bioremediation is slower in effecting positive change than chemical approaches and is contingent on the presence of calcite in soil, which is common when compared to most sodic and saline-scdic soils of arid regions. In addition, its scope becomes limited on highly sodic soils where growth of the bioremediation crops is likely to be variable and patchy and the use of chemical amendments such as gypsum is inevitable. Clearly, vegetative bioremediation is an effective low-cost intervention for resource-poor fanners. 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.

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