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Carbon sequestration in saline soils

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Abstract

Salt-affected soils cover an area of about 932 Mha, of which 56 Mha comprises secondary salinized irrigated lands. Of this, 380 Mha (~ 40%) is potentially useable for agriculture. The low net primary productivity (NPP) of salt-affected soils, due to toxic concentration of salts and deficiencies of essential nutrients and water, leads to low soil organic carbon (SOC) pool and poor soil quality. Rise in the watertable, because of changing land use and using supplemental canal irrigation without appropriate drainage, also lowers NPP. Thus, reclamation of salt affected soils can increase SOC and the terrestrial C pools, and off-set some of the anthropogenic emissions. Three technological options for reclamation include: (i) use of salt tolerant plants, (ii) agronomic techniques to improve SOC pool, and (iii) leaching of salts. Important among agronomic techniques are manuring, mulch farming with a no-till systems, establishing tree plantations or agroforestry systems, growing forages and perennial grasses, and improving soil fertility through integrated nutrient management (INM). Assuming that of the 380 Mha usable for agriculture, 100 Mha can be used for crop production and 280 Mha for tree plantations, these soils can contribute substantially to advancing food security and sequestering C. Further assuming, the short rotation woody perennials (e.g., mesquite, Acacia and Eucalyptus) can be established on 280 Mha, technical potential of C sequestration in above ground and below ground (biomass and soil) components may be 1 to 3 Mg C $ha^{-1}y^{-1}$. Thus, technical potential under plantation forestry may be 0.3 to 0.8 Pg C $year^{-1}$. Similarly, technical potential of soil C sequestration in reclaimed cropland soils may be 0.2 to 2.0 Mg C ha^{-1} $year^{-1}$ with a total potential of 0.07 to 0.2 Pg C $year^{-1}$. Therefore, total technical potential of reclaiming salt-affected soils may by 0.4 to 1 Pg C $year^{-1}$. This is an important opportunity, a cost-effective option, and a win-win situation.

Key words: carbon sequestration, management options, saline soil, soil organic carbon

Introduction

Carbon (C) sequestration, transfer of atmospheric CO_2 into other long-lived pools (geologic, oceanic, terrestrial), is an important strategy to mitigate climate change caused by increasing concentration of radiatively-active gases in the atmosphere. In contrast to the engineering techniques of geologic and oceanic sequestration, and of chemical transformations through mineralization of CO_2 into stable compounds, C sequestration in terrestrial ecosystems (i.e. soils, trees and other vegetation) is a natural process based on photosynthesis and humification of biomass. Every year, ~120 Pg (Pg = petagram = 1015g = 1 billion metric tons = 1 gigaton) of CO_2-C from the atmospheric pool is photosynthesized into biomass. Nonetheless, ~60 Pg is returned back to the atmosphere by plant respiration and the remainder 60 Pg by soil respiration. However, even if 6% to 7% of the annually photosynthesized C can be retained in the terrestrial/aquatic biosphere, it can offset the anthropogenic emissions through fossil fuel combustion estimated in 2008 at about 8 Pg C $year^{-1}$. In addition to mitigating abrupt climate change (ACC), C sequestration in soil and terrestrial ecosystems has numerous co-benefits through improvements in ecosystem services of the terrestrial biosphere which are worth several trillions of U.S. dollars.

Soil C pool has two distinct but related components: soil organic carbon (SOC) and soil inorganic carbon (SIC). The SOC pool comprises of humus and charcoal, collectively called soil organic matter (SOM), which is the sum of all organic substances in the soil. It consists of a mixture of plant and animal residues at various stages of decomposition, including by-products of microbial processes. Humus, highly decomposed fraction of SOM, is very reactive because of its large surface area and high charge density. The fossil C in soil, derived from coal such as in vicinity of coal-mines, is called "geogenic" C. The SIC pool includes elemental C and carbonate minerals (e.g., calcite, dolomite, and gypsum). There are two types of carbonates: primary and secondary. Primary carbonates are formed from the weathering of parent material. In contrast, carbonates are formed through the dissolution of CO_2 in soil water to form carbonic acid and its precipitation with bivalent cations (Ca^{+2}, Mg^{+}2) to form secondary carbonates.

The extent of salt-affected soils worldwide is estimated at about 932 million hectares (Mha), with salinity affecting 23% of arable land, and saline-sodic soils an additional 10% (Szabolcs, 1989; Gupta and Abrol, 1990, Table 1). FAO (2008) estimates that there are currently 400 Mha of salinized land, and a similar area that is affected by sodicity, a soil condition in which Na^{+} ion represents > 15% of exchangeable cations. In addition to natural salinization, secondary salinization is caused by improper use of irrigation, inhibited drainage and poor quality of water used for supplemental irrigation (Table 2). About 20% of the irrigated land area of 280 Mha (~56 Mha) in the world is affected by salinity (Yamaguchi and Blumwald, 2005). Within Europe, 26 countries are affected by salinization and sodication (Crescimanno *et al.*, 2004). The problem of secondary salinization is especially severe in developing countries of South Asia (India, Pakistan), North Africa *(Tunasia, Morocco)* and South America *(Peru, Bolivia)*. There are about 10 Mha of salt-affected soils in India of which 1.9 Mha are in U.P. (Mishra and Sharma, 2003). Out of 1 Mha of irrigation-induced waterlogged saline area in northwest India, 0.5 Mha are in the state of Haryana, leading to an annual loss in productivity of \$530 ha^{-1} and total loss in the state of \$37 million $year^{-1}$ (Datta and de Jong, 2002). In Pakistan, 4.5 to 6.0 Mha of irrigated cropland has been salinized (Qureshi *et al.*, 2008). Economic loss because of decline in production on irrigated land by salinization is estimated at \$1 billion $year^{-1}$ in Iran (Qadir *et al.*, 2008). Irrigation has also resulted in soil salinization in Central Asia in the Syr and Amu Darya basins (Funakawa *et al.*, 2000). Of the 8 Mha of irrigated area in Central Asia, 60 to 70% are moderately to severely salinized (Khakimov, 1989). Salinity is a serious problem on irrigated soils in Australia (Odeh and Onus, 2008; Wong *et al.*, 2008; Harper *et al.*, 2005).

Table 1. Global distribution of salt-affected soils (Gupta and Abrol, 1990; Szabolcs, 1979)

Continent	Land Area (106 ha)		
	Saline	Alkali	Total
North America	6.2	9.6	15.8
Mexico and Central America	2.0	-	2.0
South America	69.4	59.6	129.0
Africa	53.5	26.9	80.4
South Asia	83.3	1.8	85.1
North and Central Asia	91.6	120.1	211.7
Southeast Asia	20.0	-	20.0
Australasia	17.4	340.0	357.4
Total	343.4	558.0	901.4

Table 2. Estimates of land area (106 ha) affected by secondary salinization in South Asia (Adapted from FAO, 1994)

Country	FAO/GLASOD	Szabolcs	Dent *et al.*
	(1994)	(1979)	(1992)
Afghanistan	1.27	3.10	-
Bangladesh	0	3.02	1.30
Bhutan	0	-	-
India	4.14	23.80	7.04
Iran	32.67	27.02	21.10
Pakistan	3.83	10.46	12.00
Sri Lanka	0.05	0.20	0.70
Total	41.96	67.60	41.84

Salinization is a problem in arid and semi-arid climates where mobilization of salts within deep regolith occurs due to rise in water table. It is difficult to reverse the salinization in arid regions because good quality water that is needed for leaching the salts out of the root zone is not available. On a world scale, there are some 380 Mha of salt-affected soils that are potentially usable for agriculture (Lambers, 2003). These soils occur in arid regions where evaporation exceeds precipitation for most of the year.

Salt affected soils also occur in the Arctic regions. Frozen saline sediments are widely distributed along the Russian Arctic coast and in other Cryosols (Brouchkov, 1998; 2002). These soils occupy the position between frozen and unfrozen soils and contain ≥ 0.05% by weight of soluble salts (Williams and Smith, 1989; Ershov, 1998). Because of their high SOC concentration, global warming may thaw these soils and make them a major source of CO_2 because of the positive feedback. The source of the salts in these frozen soils is sea, marine, glacial-marine, shallow water and lagoon deposits. Principal types of salinization processes include: (i) redistribution of water and salts during the diagnosis of the sedimentary deposits, and (ii) variable freezing and thawing.

Salinization, both primary and secondary, is a major threat to agriculture, net primary productivity (NPP), and the environment. About 100 Mha or 5% of arable land is adversely affected by high salt concentration, and has low agronomic yields. A survey conducted between 1993 and 1995 in the Sacramento Valley in California revealed a loss of 10% in crop yield as the salinity increased by 1 dS m^{-1} (Rozema and Flowers, 2008). Crop yields in salinized soils of Kazakhstan has decreased by 30 to 33% (Khakimov, 1989). Low NPP in salt-altered soils is attributed to numerous adverse edaphic factors that limit plant growth. High concentration of Na^+, Mg^{+2}, Cl^-, SO_4^{-2} ions is one of the factors. In addition to salt toxicity and elemental imbalance, adverse soil physical conditions in the root zone (e.g., sodic soils) and waterlogging (Datta and de Jong, 2002) also inhibit plant growth.

Because of decline in NPP and prevalence of other degradation processes, salt effected soils have lower SOC pool than non saline soils. Low SOC concentration in the root zone exacerbates some of these problems especially those related to poor aggregation. Consequently, salt affected soils are depleted of their SOC pool. In NSW, Australia, Wong *et al.* (2008) reported that SOC pools to 0.3 m depth were 35-54 Mg ha^{-1} in soils vegetated with native pastures compared with 20 Mg ha^{-1} in scalded profiles and only 8 to 11 Mg ha^{-1} in scalded-eroded profiles. In addition to low quantity of SOC pool, quality and stability of humic substances is also affected by salinity. Peinmann *et al.* (2005) observed in a Typic Natraquoll in Argentinean Pampas that bioturbation into deeper layers was restrained, and there was less alteration of lignin. High pH and predominance of monovalent cations (e.g., K^+, Na^+) decreased formation of solid organo-mineral complexes. Relative concentrations of hydrophilic and hydrophobic fractions, affected by salinity and sodicity and as detected by fluorescence spectroscopy (Cilenti *et al.*, 2005), is also low in salt-affected soils.

Depletion of the SOC pool in salt affected soils has created a C sink capacity which can be realized through restoration and adoption of recommended management practices (RMPs). Therefore the objective of this manuscript is to describe land use and management options which can enhance the SOC pool in salt affected soils. With large areas and the need for restoring these soils, an attempt is also made to assess the global potential of SOC sequestration through restoration, land use conversion and adoption of RMPs in salt affected soils.

Carbon management in salt affected soils

Despite the areal extent of salt affected soils worldwide, the research information on SOC pool and flux under different management systems is rather scanty (Wong *et al.*, 2008). There are 3 strategies to reclaim salt affected soils (Fig. 1): (i) enhance tolerance to high salt concentration either by choosing salt tolerant species or by enhancing tolerance to excess salts by selective breeding, (ii) improve SOC concentration because even the slightest increase can have a major positive impact on soil structure, aeration, permeability, water retention and microbial/enzymatic reactions, and (iii) accelerate soil desalinization by leaching excess salts out of the soil profile and root zone through improved drainage and irrigation with a good quality water. This paper primarily focuses on the first two strategies because of their positive effect on the SOC pool.

Salt tolerance

Establishing vegetation cover is essential to enhance the low SOC concentration in salt affected soils because of little or no biomass addition. Establishment of plants increases SOC concentration by: (i) addition of leaf litter, (ii) growth and turnover of root biomass, (iii) addition of root and mucilage exudates, and (iv) increase in activity of soil fauna especially microbial biomass. Some plant species are naturally adapted to saline conditions. Most terrestrial plants evolved in saline ocean water with high salt concentration of about 500 mmol l^{-1}. However, most species adapted to terrestrial environments with low salt concentrations about 450 million years ago (Rozema and Flowers, 2008). Yet, only about 1% of the species growing under terrestrial environments have retained tolerance to high salt concentrations. These species, called halophytes, have a wide range of phonological characteristics, and include cereals, legumes, annuals, perennials, shrubs, trees etc. Qadir *et al.* (2008a) reported that there are 16 major halophytic plant families in Iran. These families in terms of salt tolerance are in the order *Chenopodiaceae>Poaceae>Asteraceae>Brassucaceae>Plumbaginaceae>Cyperaceae> Tamaricaceae>Zygophyllaceae>Polygonaceae>*other families. The growth rate of halophytes are comparable to those of conventional plants. Some useful halophytes, which can be used for industrial purposes and biofuel production, are listed in Table 3. Halophytes can also be grown under arid conditions by irrigation with saline water, or mixing saline water with fresh water. In addition to exploration of natural genetic variations, development of transgenic plants is another options to enhance the degree of salt stress or tolerance (Yamaguchi and Blumwald, 2005).

Techniques to enhance the SOC pool

Even at a low concentration, SOC is important to improving soil fertility, increasing water permeability, enhancing aggregation, and accentuating soil biotic activity. Thus, SOM is an important indicator of soil quality and the ecosystem services that it provides. Improving SOC pool is an important strategy of reclaiming salt affected soils. The goal is to create a positive ecosystem C budget (Fig. 1). There are several technologies which have proven effective in enhancing the SOC pool. Some of these are briefly discussed below:

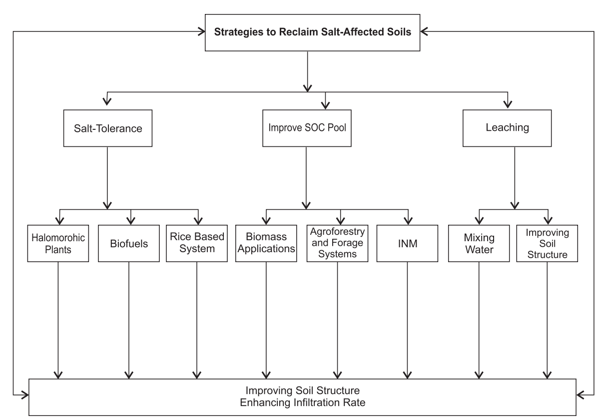

Fig. 1. Strategies to reclaim salt affected soils

Manuring

Application of manure can enhance the SOC pool in salt affected soils, increase microbial activity in the rhizosphere, and positively impact cycling of C, N, P, S, and other elements (Liang *et al.*, 2005). Restoration, while reducing salt concentration, also leads to improvements in nutrient availability while increasing the SOC pool, especially through the addition of the root biomass (Hua *et al.*, 2008). In addition

Table 3. Some salt tolerant plants

	Plant		Latin Name	
I	Fruit trees			
		Tamarind	*(Tamarindus indica)*	
		Mango	*(Mangifera indica)*	
		Loquat	*(Eriobotrya japonica)*	
		Jamun	*(Syzygirum cuminii)*	
		Coconut	*(Cocos nucifera)*	
		Oil Palm	*(Elaeis guineensis)*	
		Guava	*(Psidium guajava)*	
II	Halophytes			
		Pickle weed	*(Salicornia spp) Turtle weed*	*Batis maritima*
		Salt Grass	*(Distichlis palmeri) Seep weed*	*Suaeda esteroa*
		NyPa Forage	*(Distichlis spp)*	*Sesuvium portulacastrum*
		Salt bushes	*(Atriplex nummularia)*	
		Algae	*(Spirulina geitleri)*	
III	Trees			
		Gum trees	*(Eucalyptus spp)*	
		Acacia	*(Acacia spp)*	
		Shisham	*(Dalbergia sissoo)*	
		Ye-eb	*(Cordeeauxia edulis)*	
		Pine	*(Pinus oocarpa)*	
		Mesquite	*(Prosopis juliflora)*	
		Jojoba	*(Simmondsia chinensis)*	
		Casuarina	*(Casuarina equisetifolia)*	
		Albizia	*(Albizia lebbeck)*	
		Ber	*(Zizyiphus mauritiana)*	
		Arjuna	*(Terminalia arjuna)*	
IV	Grasses and Forages			
		Karnal Grass	*(Leptochloa fusca)*	
		Vetiver	*(Vetiveria spp)*	
		Narrow Leaf Lupin	*(Lupinus angustifolius)*	
		Wheat grass	*(Thynopyron ponticum)*	
V	Crops			
		Triticale	*(Secale spp)*	
		Bambara groundnut	*(Voandzeia subteranea)*	
		Marama bean	*(Tylosema esculentum)*	
		Tepary bean	*(Phaseolus acutifolius)*	

to soil fertility, soil structure is also improved in salt-affected soils amended with biosolids. Most soils of the arid regions have low SOC concentrations ranging from 0.03 to 3.0 g kg^{-1}, compared with SOC concentration in animal manure at >300 g kg^{-1} (Zahoor *et al.*, 2007) Therefore, application of manuring and organic amendments enhances SOC pool (Garcia-Orenes *et al.*, 2004). In Southern Spain, Garcia-Ornes *et al.* (2004) observed increase in aggregation and aggregate stability with application of organic amendments. Use of successive applications of poultry manure, however, can increase the risks of secondary salinization (Li-Xian *et al.*, 2007), and the effect is more severe in greenhouse vegetable production (Shi *et al.*, 2009). Salt concentration in the animal manure is in the order pigeon manure > chicken manure > pig manure (Table 4). In general, cattle manure has low salt concentration.

Table 4. Salt concentrations in some animal manure (Adapted from Li-Xian *et al.*, 2007)

Manure	Salt concentration (g kg^{-1})	Coefficient of variation (%)
Chicken	49.0 ± 18.8	38.4
Pig	20.6 ± 6.9	33.5
Pigeon	60.3 ± 19.3	32.0

Table 5. Effect of crop residue management on the quality of a saline and saline-sodic soil Northeast Spain (Recalculated from Badia, 2000)

Soil	Residue management	EC (dS m^{-1})	SAR (mmol l^{-1})1/2	Infiltration rate (mm h^{-1})	Bulk density (Mg m^{-3})	Aggregate stability (g Kg^{-1})	Soil organic carbon		
							g Kg^{-1}	Mg ha^{-1}	Mg C ha^{-1} $year^{-1}$
Saline	Removed	12.1a	6.1a	12.6b	1.44a	242b	4.4b	9.82	-
	Incorporated*	4.9b	5.7a	78.0a	1.33b	322a	5.6a	11.17	0.68
Saline-sodic	Removed	12.9a	16.1a	10.2a	1.37a	263a	4.7b	9.66	-
	Incorporated	6.6b	14.7a	15.0a	1.27b	287a	6.7a	12.76	1.55

*Straw Incorporated@ 6Mg ha^{-1}, Soil depth = 15 cm

Crop residue management

Conservation tillage/no-till (NT) system, mulch farming, and crop residue mulching are important to increase SOC concentration in salt affected soils, enhancing water transmission and structural properties, and reversing the salinization process (El-Tayeb and Skujins, 1989). In the Centro Ebro Valley of NE Spain, Badia (2000) reported that application of barley (*Hordeum vulgare*) straw at 6 Mg ha^{-1} increased SOC concentration and pool and enhanced soil physical properties even over a short 2-year period (Table 5). The rate of SOC sequestration over the 2-year period was 0.68 Mg C $ha^{-1}year^{-1}$ in a saline soil and 1.55 Mg C $ha^{-1}year^{-1}$ in a saline-sodic soil (Table 5).

Mulching with crop residues is usually done in conjunction with a NT system. Use of crop residue mulch in conjunction with NT farming, and incorporation of cover crops in the rotation cycle, improves soil structure, increases aeration, and enhances soil physical quality especially of the surface layer. Direct seeding of wheat *(Triticum aestivum)* after rice *(Oryza sativa)*, being rapidly adopted throughout the Indo-Gangetic Basin for the rice-wheat system (Hobbs and Gupta, 2004), has ameliorative effects on properties of soils and on yield of wheat sown directly through the rice stubbles. Saving in time for seedbed preparation, saving in energy and higher and better quality yield of wheat sown early are important co-benefits of this system to the small-scale farmer of the South Asian region.

Establishing tree plantations

Rapid salinization since the World War II (~ 1940s) has partly resulted from increased recharge following the wide spread clearing of perennial native forests and woodlands and their replacement by annuals which use less water. Such a drastic land use change has raised the watertable and increased salt concentration in the root zone (Farrington and Salma, 1996). Thus, establishing trees in waterlogged soils is important to lowering the watertable. Recharge must also be reduced to prevent any further rise in salts. In this regards, planting trees is one of the most favorable options (Farrington and Salma, 1996). Trees, forming a component of complex agricultural systems (Qadir *et al.*, 2008b) are, important to moderating the watertable and restoring salt affected soils. It has been widely documented that reforestation by trees on cleared lands have greatly lowered groundwater levels compared with adjacent agricultural lands (Bari and Schofield, 1992). Several trees are suited for establishment in salt-affected soils (Table 3). Leguminous trees *Prosopis juliflora* and *Dalbergia sissoo* are adapted to degraded sodic soils of northwest India (Mishra and Sharma, 2003, Gupta and Rao, 1994). *Eucalyptus spp*. grows under diverse conditions, including sodic soils in India (Mishra *et al.*, 2003), and Australia (Lambers, 2003). In Iran, *Tamarix* and *Atriplex plantations* are effective in decreasing salinity. Other trees found suitable for growing on salt affected soils in Iran are *Haloxylon aphyllum, H. persicum, Petropyrum euphratica* (Qadir *et al.*, 2008a; b). *Atriplex* is a potential fodder shrub. Evergreen and deep-rooted trees transpire a large quantity of water, lower the watertable, and improve aeration in the root zone. Furthermore, deep-rootedness of trees allows the access to soil moisture in arid environments whereas the shallow-rooted annuals suffer from drought stress. Thus, establishing trees on salt affected soils provides a long-term solution for managing the dryland salinity problem (Ward *et al.*, 2003; Lambers *et al.*, 2003).

Agroforestry systems

Tree-based and complex ecosystems based on growing deep-rooted plants (e.g., trees and perennial pastures) are agroforestry techniques are important to reclaiming salt affected soil (Stirzaker *et al.*, 2002). The data in Tables 6 and 7 from U.P. India, show high rates of SOC sequestration in sodic soil planted to Eucalyptus. There was a measurable increase in SOC pool to 150 cm depth. The rate of SOC sequestration was 1.1 to 1.5 Mg C ha^{-1} $year^{-1}$ (Tables 6 and 7). Similar to crops, trees can also be grown in association with pastures through agroforestry systems. The strategy is to restore complexity and resilience in pastoral systems (Hobbs and Cramer, 2003; Lambers, 2003). Deep-rootedness of trees is important to incorporating the SOC pool in the sub-soil and enhancing soil structure. Perennials with deep root system also use more water than shallow-rooted annuals and can improve the drainage conditions. Agroforestry systems are being proposed at a large scale for reclamation of 8.8 Mha of salt-affected soils in South-western Australia. Harper *et al.* (2005, 2007) estimated that rates of C sequestration in biomass of *E. globulus* over a 10 year period range from 3.3 to 11.5 Mg C ha^{-1} $year^{-1}$ (Table 8). These are extremely high rates of C sequestration, especially on a large scale watershed. Experiments conducted in the Indo-Gangetic plains showed that growing mesquite (*Prosopis juliflora*) and other perennials is

Table 6. Changes in bulk density and organic carbon concentration and pool under Eucalyptus plantations in a sodic soil of U.P. India (Recalculated from Mishra *et al.*, 2003)

Treatment	Soil Depth (cm)	SOC Concentration (g kg^{-1})	Bulk density (Mg m^{-3})	SOC Pool (Mg ha^{-1})	Rate of SOC sequestration (Mg C ha^{-1} $year^{-1}$)
1. Control					
	0-10 (10)	2.0	1.66	3.32	
	10-30 (20)	1.6	1.59	5.09	
	30-60 (30)	0.9	1.66	4.48	
	60-90 (30)	0.6	1.72	3.10	
	90-120 (30)	0.6	1.74	3.13	
	120-150 (30)	0.3	1.76	1.58	
	Total			20.70	Baseline
2. Three year old Plantation					
	0-10 (10)	3.2	1.39	4.45	
	10-30 (20)	2.2	1.39	6.12	
	30-60 (30)	1.2	1.48	5.33	
	60-90 (30)	0.8	1.56	3.74	
	90-120 (30)	0.7	1.63	3.42	
	120-150 (30)	0.3	1.67	1.50	
	Total			24.56	1.29
Plantation					
	0-10 (10)	4.2	1.27	5.33	
	10-30 (20)	2.8	1.27	7.11	
	30-60 (30)	1.0	1.38	4.14	
	60-90 (30)	0.6	1.45	2.61	
	90-120 (30)	0.7	1.52	3.19	
	120-150 (30)	1.0	1.57	4.71	
	Total			27.09	1.07

Table 7. Changes in bulk density and organic carbon concentration and pool under Eucalyptus plantations in a sodic soil of U.P. India (Recalculated from Mishra *et al.*, 2003)

Treatment	Soil depth (cm)	SOC concentration (g kg^{-1})	Bulk density (Mg m^{-3})	SOC pool (Mg ha^{-1})	Rate of SOC sequestration (Mg C ha^{-1} $year^{-1}$)
1. Control					
	0-10 (10)	4.2	1.54	6.46	
	10-30 (20)	2.8	1.48	8.29	
	30-60 (30)	1.0	1.45	4.35	
	60-90 (30)	0.6	1.52	2.74	
	90-120 (30)	0.7	1.40	2.94	
	120-150 (30)	1.0	1.50	4.50	
	Total			29.28	Baseline
2. Nine year old Plantation					
	0-10 (10)	12.8	1.01	12.93	
	10-30 (20)	6.6	1.01	13.33	
	30-60 (30)	2.3	1.01	6.97	
	60-90 (30)	0.9	1.07	2.89	
	90-120 (30)	0.8	1.09	2.62	
	120-150 (30)	1.1	1.18	3.89	
	Total			42.63	1.48

Table 8. Estimate of C sequestration rates in salt affected soils of the Collie catchment (Recalculated from Harper *et al.*, 2005)

Sub-catchment	Carbon sequestration rate (Mg C $ha^{-1}year^{-1}$)	
	Low	High
Bingham River	3.8	5.2
Collie River Central East/James Well	3.8	5.2
Collie River East	3.3	4.4
Collie River South Branch	4.6	6.0
Harris river	8.5	11.5
Wellington Reservoir/Collie River Central	6.6	9.0

Table 9. Increase in soil organic carbon (SOC) concentration (%) of an alkali soil in northwestern India by growing *Prosopis juliflora-Leptochloa fusca* system (Singh *et al.*, 1994)

Time	0-15 cm Depth		15-30 cm depth	
(months)	Prosopis	Prosopis + grass	Prosopis	Prosopis + grass
0	0.18	0.19	0.13	0.12
22	0.20	0.28	0.12	0.16
52	0.30	0.43	0.19	0.21
74	0.43	0.58	0.29	0.36

an effective strategy for increasing the SOC pool in salt-affected soils. The data in Table 9 show that establishing mesquite on an alkaline soil in NorthWestern India increased its SOC concentration over a 74-month period from 0.18% to 0.43% in 0-15cm depth, and from 0.13% to 0.29% in 15-30 cm depth. Establishing mesquite in association with Kallar grass (*Leptochloa fusca*) increased SOC concentration over a 74-month period from 0.19% to 0.58% in 0-15cm depth compared with 0.12% to 0.36% in 15-30 cm depth (Table 9). The data in Fig. 2 from Garg (1998) show increase in SOC pool from about 10 Mg ha^{-1} to > 45 Mg ha^{-1} after a 5 year period under *Acacia nilotica* and about 40 Mg ha^{-1} under *Dalbergia sissoo.* In addition to lowering the watertable or enhancing aeration and improving the SOC pool, there are other ecosystem services provided by the choice of appropriate agroforestry systems. Agroforestry techniques advance sustainable management of soil resources, especially of salt-affected soils with numerous physical and chemical/ nutritional constraints to high agronomic production. Other benefits include use of woody biomass as fuel source, increase in biodiversity, and increase in NPP. Bioremediation of a sodic soil by silvopastoral system, has proven effective in soils of northwestern India (Kaur *et al.*, 2002).

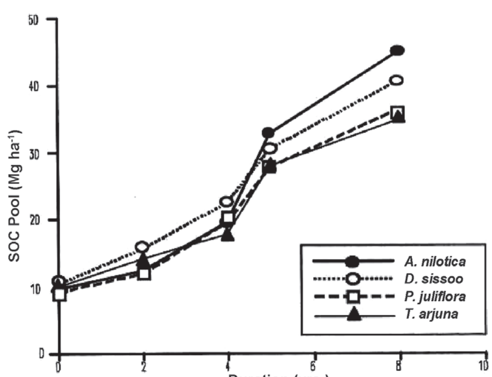

Fig. 2. Carbon sequestration through reclamation of salt affected soils in northern India (Recalculated from Garg, 1998 and Lal *et al.*, 1998)

Perennial grasses and pastures

Similar to the beneficial effects of trees, establishing deep-rooted grasses also enhance the SOC pool and reclaim salt-affected soils. In NSW, Australia, Wong *et al.* (2008) reported that SOC concentration was significantly higher in the profiles that were vegetated with native pastures (1.96-2.71% in the 0-5 cm layer) or re-vegetated with sown pastures (2.35% in the 0-5 cm layer) than in profiles that were scalded (1.52% in 0-5 cm layer). Several studies have shown that growing Karnal/Kallar grass has strong ameliorative effects. In Pakistan, Akhter *et al.* (2004) observed strong positive effects of growing Kallar grass for 3 years on soil physical properties, especially the plant-available water capacity, hydraulic conductivity, and structural stability. Improvement in soil physical properties was positively correlated with the SOC concentration. The data in Table 10 from Pakistan indicate increase in duration of establishing Kallar grass decreased linearly soil bulk density up to 100 cm depth. There was also an increase in plant-available water capacity and saturated hydraulic conductivity with increase in duration of establishing the Kallar grass (Table 10). Wong *et al.* (2008) reported that profiles that were vegetated with native pastures contained 35.2-53.5 Mg C ha^{-1} to 30-cm depth compared with 42.1 Mg C ha^{-1} in sown pastures, only 19.8 Mg C ha^{-1} in scalded profile, and 7.7 to 11.4 Mg C ha^{-1} in scalded-eroded soils. Regardless of the antecedent concentration, SOC pool in young pastures reaches values observed in old pastures, and the increase can persist for about 40 years (Contant *et al.*, 2001). Wong *et al.* (2008) observed that SOC pool in re-vegetated pastures increased to a level comparable to that under native pastures. Similar improvements in SOC concentration are reported from Argentina (Table 11).

Integrated Nutrient Management

High salt concentration and nutrient deficiencies are the main factors which adversely affect NPP in salt

Table 10. Effect of Kallar grass on physical properties of a salt-affected soil in Pakistan (Adapted from Akhter *et al.*, 2004)

Duration (Yr)	Plants Available Water (cm)			Soil Bulk Density (Mg m^{-3})		
	0-20 cm	40-60 cm	80-100 cm	0-20 cm	40-60 cm	80-100 cm
0	5.0	5.2	5.1	1.62	1.73	1.68
1	5.6	6.0	5.4	1.61	1.72	1.60
2	5.8	6.0	5.8	1.58	1.65	1.59
3	6.0	6.1	6.2	1.55	1.59	1.56
4	6.7	6.1	6.5	1.54	1.53	1.55
5	6.5	6.2	6.5	1.53	1.53	1.54

Pb = 1.672 – 0.031 D, R2 = 0.96 **, Pb = mg m-3 D = Duration (yr) Ks = 2.07 D2.007, R2 = 0.98, Ks = mmd-1

Table 11. Soil organic carbon and total nitrogen concentration of some salt affected soils in Pampa, Argentina (Recalculated from Peinemann *et al.*, 2005)

Soil Type	Land use	Depth (cm)	Salinization	SOC conc. (g kg^{-1})	TN conc. (g kg^{-1})	C:N ratio
I. Chascomu's						
Aquic	Natural	0-3	Non-Saline/	38a	3.3a	11.5a
Argiudoll	Grassland	3-6	Non-sodic	35b	3.2a	11.1a
		6-9		32b	3.1a	10.4a
Typic	Natural	0-3	Non-Saline/Sodic	25a	2.2a	11.2a
Natraquoll	Grassland	3-6		16b	1.6b	10.2a
		6-9		13c	1.1c	11.0a
II. Balcarce						
Petrocalcic	Arable	0-6	Non-Saline/	39a	3.3 a	11.8a
Paleudoll		6-21	Non-sodic	33b	2.8 a	11.8a
		21-30		34b	2.8a	12.2a
2. Typic	Natural	0-6	Saline/Sodic	46a	4.4a	10.5a
Natralboll	Grassland	6-15		20b	1.8b	10.9a
		15-22		13c	1.0b	12.9a

SOC = Soil Organic Carbon

TN = Total Nitrogen Figures in the column for the same soil and land use followed by similar letter are statistically similar.

affected soils. Therefore, balanced application of essential plant nutrients, macro (N, P, K) and micro (Zn, Cu, B) is essential for good plant growth and agronomic yields. Further, increased salinity reduces availability and uptake of both water and nutrients, reducing NPP. Application of P is especially important to improving plant growth in salt affected soils (Zahoor *et al.*, 2007). Application of P increases root growth which also enhances the SOC pool and alleviates drought stress.

Leaching of soluble salts

Leaching with good quality irrigation water is important in reducing/diluting salt concentration in the root zone. Thus, bioirrigation and bioturbation are essential to soil restoration (Canavan *et al.*, 2006). In this context, incorporation of rice in the rotation cycle is a useful practice. Assessing the leaching requirements provides a useful guide to determine the amount of water needed for achieving the desired effect. Leaching of the excess salts out of the root zone can enhance crop growth and yields. Field experiments in Iran have indicated the positive effects of leaching on relative grain and stover yield of barley. Effectiveness of leaching is also enhanced by application of soil amendments (e.g., gypsum), and acidifying *Thiobacilus* microorganism (FAO, 2000). In a mountainous oasis of northern Oman, Luedeling *et al.* (2005) concluded that sustainability of an irrigated land use system is primarily due to high water quality with low Na^+ but high $CaCO_3$ concentration. It is this high quality of irrigation water that is responsible for good soil structure, favorable internal drainage, and lack of salinization. Manuring, rather than heavy use of chemical fertilizers is also useful in maintaining a favorable structure.

Growing halophytes as biofuel reedstocks

Strongly and extremely degraded soils must be taken out of the agricultural and pastoral land uses and planted to dedicated trees, shrubs or grass species that it can be used as biofuel. The biomass can be used as direct fuel for power generation. Total land area of strongly and extremely

Table 12. Mean annual biomass yield and C sequestration rate of sea-water irrigated halophytes at Puerto Penasco, 1990-1992 (Modified from Glenn *et al.*, 1993)

Species	Biomass yield	C sequestration rate*
	------Mg C ha^{-1} year^{-1}------	
Batis maritime	34.0	8.2
Atriplex linearis	24.3	6.7
Salicornia bigelovii		
year one	22.4	5.6
year two	17.7	4.3
Suaeda esteroa	17.2	4.3
Sesuvium partulacastrum	16.7	4.2

*Based on net primary production (NPP)

degraded soils can be planted to energy plantations. In addition to salt affected soils, some water reserves are saline (brackish) with high salt content ranging from 5000 to 40,000 ppm. While common crops cannot tolerate such high salt concentrations, some halophytes are adapted to such conditions. A major opportunity for biotechnology lies in developing new germplasm that is tolerant to high salt concentration in the root zone, and has high NPP in harsh environments. Such engineered germplasm might also be made to biodegrade slowly. Examples of some useful halophytes shown in Table 3 indicate vast potential of producing high-grade fodder, forage, oil, and food. Experiments show that halophytes irrigated with seawater can produce biomass yield of 17 to 35 Mg ha^{-1} year^{-1} with a net C sequestration rate of 4-8 Mg ha^{-1} year^{-1} (Table 12). Further, the residence time of C in drylands is much longer and the decomposition rate much slower than that in humid environments (Gifford, 1974; Gifford *et al.*, 1992).

Potential of carbon sequestration in salt affected soils

There are 380 Mha of salt affected soils which are potentially useable for agricultural production. Of this, 56 Mha are affected by secondary salinization because of inappropriate irrigation practices. Technologies for reclamation of salt affected soils are available, and have been proven effective in diverse soils and environments. Of these, manuring, mulch farming, establishing salt-tolerant forages and grasses, afforestation, agroforestry measures, use of gypsum and other amendments are extremely effective in improving NPP and enhancing SOC pool. The rate of SOC sequestration can be as high as 0.5-2 Mg C ha^{-1} year^{-1}. Even if the rate of biomass production, in arid environments with poor availability of water and nutrients, is low at 0.5^{-1} Mg C ha^{-1} year^{-1}, total ecosystem C pool can be enhanced at 1-3 Mg C ha^{-1} year^{-1}. Assuming that 100 Mha of reclaimed soils can be used for crop production and 280 Mha for afforestation/perennial vegetation, technical potential of C sequestration is 380 Mha is 0.4-1.0 Pg C year^{-1}. If economic and realizable potential is 66% of the technical potential, reclamation of salt affected soils can off-set anthropogenic emissions at the rate of 0.25 to 0.66 Pg C year^{-1} for about 50 years.

Conclusions

The severe problem of salinization in arid and semiarid regions is attributed to land use conversion involving deforestation, excessive irrigation, poor drainage and use of brackish water for irrigation. Poor drainage and rise in watertable are among the principal causes. Adoption of scientifically proven technologies can increase NPP and enhance ecosystem C pool as humus in soils and woody/perennial material as above ground biomass. About 40% of the global land area affected by high salt concentration can be reclaimed and used for agricultural production. Of the 380 Mha of useable land area, 100 Mha can be used for crop production and 280 Mha for perennial land use through afforestation and establishment of forages and grasses. Technical potential of terrestrial C sequestration is 0.4-1.0 Pg C year^{-1} for about 50 years. If C sequestered in terrestrial ecosystems can be traded either through CDM or voluntary market, the additional income generated is an important incentive for the land managers to adopt RMPs. In addition to off-setting anthropogenic emissions, reclamation of salt affected soils is also an important strategy to advance global food security and achieve U.N. Millennium Development Goals.

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Key words: gypsum, *Oryza sativa* L., rice, salt tolerance,

Tables and figures

Each table and figure should have 12 font and be given on separate page after References part. Table 1 and Figure 1 should be written as **Table 1** (bold) and **Fig. 1** (bold), respectively. Table caption should appear on the top of table whereas figure caption should be just below the figure. Figures captions and matter should be legible with 8-12 font size. Maximum size of tables and figures should be such that these can be conveniently accommodated in A4 size page. Approximate position of the tables and figures should be indicated in the text of the manuscript.

References

References should be in alphabetic and chronological order and should not be serial numbered. The author(s) names should start with surname, comma followed by initials. If first author has two publications in a year, single author paper should appear first. Year should not be bracketed. The journal names should be in full without abbreviation and should be italicized. Volume No. should be in bold. Few examples are given below:

Journal: Qadar, A. and Ansari, Z.M.A. 2006. Phosphorous requirement of rice grown in soils with different sodicity. *Journal of Plant Nutrition* **29**: 2105-2117.

Book: Biswas, T.D. and Mukherjee, S.K. 1989. *Text Book of Soil Science*, Second Edition, Tata McGraw-Hill Publishing Company Limited, New Delhi.

Book Chapter: Wojcik, P. 2003. The importance of boron in apple production. In: *Crop Management and Post Harvest Handling*. Vol. III-*Crop Fertilization, Nutrition and Growth* (Eds. Dris, R., Niskanen, R. and Jain, S.M.), pp 77-92. Enfield, New Hamp: Science Publishers Inc.

Online reference: FAO 2008. *FAO Land and plant nutrition management service*. http://www.fao.org/ag/agl/agll/spush.

Conference/Symposium Proceedings: Eichert,T.J. and Burkhardt, J. 1999. A novel model system for the assessment of foliar fertilizer efficiency. In: *Technology and Applications of Foliar Fertilizers. Proceedings of the Second International Workshop on Foliar Fertilization*, Bangkok, April 4-10. The Soil and Fertilizer Society of Thailand. pp 41-54.

***M.Sc./Ph.D. Thesis*:** Ammar, M.H.M. 2004. Molecular Mapping of Salt Tolerance in Rice. *Ph.D. thesis*, Indian Agricultural Research Institute, New Delhi, India.

Bulletin: Singh, Gurbachan. 2008. *Managing Prosopis for Livelihood Security in Salt Affected and Dry Areas*. *Technical bulletin*: CSSRI/Karnal/2008/10. Central Soil Salinity Research Institute, Karnal, 30 p.

Short communication: These should focus on studies of limited scope, preliminary data, unique observations or research techniques and apparatus. The length of a Short communication should not exceed 3 published pages. Short communication should comprise of Short Title, Title, Material and methods, Results and discussion. It may not have Abstract, Key words.

Book Review: These are generally invited, however, one may send critical Book Review along with one original book for consideration by editorial board.

Units to be followed

The International system of Units (SI units) should be used throughout. Authors may consult Clark's Tables: Science Data Book by Orient Longman, New Delhi (1982) for guidance:

The terms like Nitrogen, Phosphorus, Potassium and Zinc may be denoted as N, P, K and Zn, respectively and dose expressed as kg ha^{-1} for field experiments. For pot studies, units like mg kg^{-1} should be followed.

Common units and symbols

time=t, metre=m, second=s, centimeter=cm, cubic centimeter=cm^3, cubic metre = m^3, degree Celsius=°C, day=d, gram=g, hectare=ha (10^{4}m^2), Hour=h, Kilometer=km, Kilogram=kg, litre=l, Megagram=Mg (tons to be given in Mg), Microgram=µg, Micron=µm, milimole=mmol, milliequivalent=meq, micromol=µmol, milligram=mg, milliliter =ml, minute=min, nanometer=nm, square centimeter=cm^2, square kilometer = km^2, electrical conductivity (EC)=dS m^{-1} (deci Siemens m^{-1}), gas diffusion=g m^{-2} s^{-1}, water flow= m^3 m^{-2} s^{-1}, ion uptake= mol kg^{-1} of dried plant material, leaf area= m^2 kg^{-1}, nutrient content in plants= mg g^{-1} (dry matter basis), root density or root length density=m m^{-3}, soil bulk density=g cm^{-3}, transpiration rate= mg m^{-2} s^{-1}, water content of soil=kg kg^{-1}, water tension= kPa, yield (grain or forage)= Mg ha^{-1}, organic carbon content of soil= percent (%), cation exchange capacity of soil=cmol (p+) kg^{-1}.

Style guidelines

All soils discussed in the manuscript should be identified according to the U.S. Soil Taxonomic System at first mention. The Latin binomial or trinomial and authority must be shown for all plants, insects, pathogens, microorganisms and animals when first mentioned. Both the accepted common name and the chemical name of any chemicals mentioned (including pesticides) must be provided. SI units must be used throughout the manuscript. Corresponding metric or English units may be added in parentheses at the discretion of the author. For spelling, Webster's *New Collegiate Dictionary* should be used as reference. If a commercially available product is mentioned, the name and location of the manufacturer should be included in parentheses after first mention. Responsibility of the facts and opinions expressed in the articles rests entirely with the author(s) and not with the journal.

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