Harnessing Salt Affected Soils for Sustainable Crop Productivity

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Introduction

'Salt-affected soils' (SAS) is an umbrella term to designate the soils having either excess soluble salts and/or exchangeable sodium. Based on the values of soil saturation paste extract electrical conductivity (EC_e), pH (pH_s) and exchangeable sodium percentage (ESP), soils are classified into normal, saline, sodic and saline-sodic. However, there are no universally accepted threshold values of these parameters resulting in different classification schemes for SAS in different countries. For example, in Australia, soils with ESP between 6 and 14 are designated as sodic while those having ESP >15 are classified as 'strongly sodic' (Rengasamy, 2006). This is in contrast to both India and the United States where soils with ESP >15 are considered sodic. Similarly, soils having pH_s values >8.5 and >8.2 are considered sodic in the United States and India, respectively. In India, pH_s value of 8.2 has been found to be more realistic than 8.5 due to a strong correlation (r= 0.87-0.97) between soil pH_s 8.2 and ESP 15 in the sodic soils of IGP. Classification of SAS in India is also different from USA. In India, only two categories (saline: EC_e ≥4 dS m^{-1}, pH_s <8.2, ESP <15; and sodic: EC_e <4 dSm^{-1}, pH_s >8.2, ESP >15) are adopted, while SAS are classified into three categories (saline, sodic and saline-sodic) in USA (Minhas, 2010).

About 20% of the global crop lands have become less productive or, in extreme cases, uncultivable wastelands due to waterlogging and salinization. Presence of salty water in root zone virtually transforms the affected lands into wetland deserts. Soils in many rainfed areas are also reeling under the combined impacts of erosion, salinization and fresh water scarcity. A recent estimate suggests that over 1100 Million hectare (M ha) of global land area is affected by salinity and related problems to varying extents. Certain regions/countries such as Middle East (189 M ha), Australia (169 M ha) and North Africa (144 M ha) suffer from a very high degree of salinization. In South Asia (including India), about 52 M ha area is salt-affected. Despite relentless salinity onslaught (irrigation-induced salinization affects 0.25-0.5 M ha area annually), the fact remains that a large chunk (≈85%) of global SAS have only mild to moderate limitations that can easily be overcome by suitable technological interventions (Wicke *et al*., 2011).

In India, ≈120 M ha land suffers from one or another kind of degradation: soil erosion (94.9 M ha), salinity and sodicity (6.74 M ha), soil acidity (17.94 M ha) and other stresses (1.07 M ha) (Sharma *et al*., 2015). In saline soils, excess soluble salts consisting mainly of chlorides and sulphates of Na^+, Ca^{2+} and Mg^{2+}, raise soil EC_e (≥ 4 dS m^{-1}) resulting in reduced water availability (*i.e*., physiological drought) and specific ion toxicities responsible for growth and yield reduction in crop plants. High ESP (>15) deteriorates the structure, impedes the water and air flows, reduces water intake capacity and hampers the root penetration in sodic soils. Current estimated area under SAS (6.74 M ha; comprising of 3.79 M ha sodic and 2.95 M ha saline area) is projected to increase to 16.2 M ha by 2050. Although salt-induced crop losses are common throughout the country, only five states including Gujarat (2.23 M ha), Uttar Pradesh (1.37 M ha), Maharashtra (0.61 M ha), West Bengal (0.44 M ha) and Rajasthan (0.38 M ha) together make up ≈75% of the total SAS in India (ICAR-CSSRI, 2015).

Salinity problem has become more intricate in the past few decades as evidenced by co-existence of complex problems such as soil erosion, excess salts, nutrient toxicities and waterlogging in many situations. For example, out of 1.72 M ha irrigated area adversely affected by waterlogging (watertable lying within 2 m of the land surface) ≈1 M ha also suffers from salinity (NAAS, 2015). ICAR-CSSRI has estimated huge salt-induced losses in annual food grain, oilseed and cash crop production. While salinity diminishes ≈5.66 Million tonnes of produce valued at Rs. 8,000 Crores (Sharma *et al.* 2016a), sodicity causes annual loss of ≈11 Million tonnes (Rs. 15,000 Crores; Sharma *et al*. 2016b). Although such monetary estimates provide a reasonable approximation of the harmful impacts of salinity, basically in relation to farmers' sustenance and drain on national exchequer, it is important to understand the spill over effects that debilitate the capacity of SAS to provide a range of vital ecosystem services.

Technologies for Salinity Management

ICAR-Central Soil Salinity Research Institute (ICAR-CSSRI), Karnal was established in 1969 to develop appropriate remedial measures for enhancing agricultural production in salt-affected areas of the country.

Taking a cue from the fact that ad-hoc projects in the past did not deliver expected results, policy makers felt the need for a dedicated mission to usher in yield revolution through technology-driven improvements in the productivity of barren saline and sodic lands. In fact, establishment of ICAR-CSSRI marked a two-pronged strategy by the Government of India to safeguard country's food security: i) sustained policy support to augment food availability by large scale dissemination of '*Green Revolution Technologies*' in productive areas; and ii) additional food grain production by reviving the productivity of salt-affected wastelands.

Despite a pan-India mandate, the immediate focus was on reclaiming the sodic areas of Punjab and Haryana states so that they could also benefit from targeted initiatives made during the Green Revolution days. Successive field and laboratory experiments shortly culminated into standardization of gypsum-based package for sodic soils. By mid-1970s, it also became evident that irrigation-led yield revolution in north-western India has its own flip side: while groundwater development helped accelerate the pace of sodic soil reclamation in fresh water areas, excessive irrigation slowly turned many fertile tracts saline and sodic.

Different technologies developed by ICAR-CSSRI can broadly be categorized into four groups: '*blockbuster technologies*' like gypsum-based package, 'high impact technologies' like salt tolerant cultivars, 'least adopted technologies' like sub-surface drainage and 'incubating technologies' that are still being developed and refined for dissemination on the farmers' fields (ICAR-CSSRI, 2017b). An examination of past trends in agricultural salinity management makes it evident that in order to become popular among the farmers a particular technology should meet the criteria of '*feasibility*' (low cost and easy to adopt), '*compatibility*' (location-specific and ecologically compatible) and '*adaptability*' (amenable to refinements to suit the changing needs). Taking these considerations into account, the strengths and weaknesses of different such technologies have been discussed in the succeeding paragraphs.

Reclamation and Management of Sodic Soils

Chemical and Organic Amendments: Sodic soils of IGP owe their origin to rapid alternate wetting and drying cycles conducive to alkali hydrolysis, sodium saturation and high pH development. Nonetheless, regular irrigation with high RSC groundwater has aggravated sodicity problem in many areas. Very high water requirements of RWCS make it extremely susceptible to sodicity hazard. Soils of RWCS in IGP display almost twofold higher soil pH and ESP values compared to those under low water requiring crops like maize-wheat (Minhas and Bajwa, 2001). Because of very high water needs, application of even normal (canal) water would add ≈3-4 tons of salts ha^{-1} annually to these soils (Sharma and Singh, 2017). In the last few decades, irrigation with untreated and treated wastewater (TWW) has also increased manifold in areas grappling with fresh water shortages. However, due to relatively higher SAR compared to the fresh water of origin, soils irrigated with TWW tend to become sodic as evidenced by elevated ESP levels and subsequent clay dispersion (Bardhan *et al*., 2016). Amendment applications and other soil management practices intend basically to improve the infiltration rate (IR) and lower ESP of sodic soils. Advantages and limitations of conventional and alternative amendments for sodic soils are discussed in the following paragraphs:

Gypsum: A wide variety of chemicals, *viz*., soluble calcium salts (*e.g*., gypsum and calcium chloride), acids or acid forming substances (*e.g*. sulphuric acid, iron sulphate, sulphur and pyrite) and calcium salts of low solubility (*e.g*. ground limestone) can be used to reduce soil ESP below 15%. However, factors such as low cost, easy availability, ease of application and better efficacy compared to other chemicals have shifted the balance in favour of gypsum ($CaSO_4.2H_2O$) making it the amendment of choice to overcome sodicity-induced anomalies in soil physical conditions. Gypsum application improves the availability of exchangeable Ca^{2+} to remove surplus Na^+ from the soil exchange complex. Gypsum has been used on agricultural lands for a long time (≈250 years); as an ameliorant and as a fertilizer source of Ca and S. Gypsum also acts as a soil conditioner to minimize run-off induced soil erosion and nutrient depletion (Chen and Dick, 2011). Despite a large body of evidence from other countries showing the ameliorative effects of gypsum in sodic soils, basic studies were absolutely essential to determine the exact dose, timing and depth of application, and other management issues for desired outcomes under Indian conditions. Concerted efforts in this direction led to the development of gypsum-based package for sodic soil reclamation. Gypsum application @ 50% gypsum requirement (GR) was suggested for the traditional varieties of rice and wheat. In reclaimed lands, reduction in soil ESP was quicker and extended to the deeper depths when rice was grown as the first crop. After few years of release, this technology received an overwhelming response from the farmers and Land Development Agencies of Punjab, Haryana and Uttar Pradesh states. A number of demonstrations organized at farmers' fields further enhanced the acceptability of this practice. Gypsum reclaimed sodic lands in many parts of Haryana are still fondly designated as '*Sarkari Killa*' (an acre of sodic land reclaimed by government agencies using gypsum technology) to remember the research and policy efforts made in this direction.

Gypsum-bed technology: In areas irrigated with RSC water, gypsum use becomes necessary to alleviate the sodicity risk. Gypsum can either be incorporated into soil or put into irrigation channel (in gunny bags) such that falling tube well water will slowly dissolve the gypsum. However, use of specifically constructed gypsum-dissolving beds for this purpose gives far better results (Tyagi, 2003). In gypsum-bed method, irrigation water is passed through a brick-cement chamber containing gypsum clods. Size of the chamber depends on the rate of tube well discharge and RSC of irrigation water. This chamber is connected to a water fall box on one side and to water channel on the other. A net of iron bars covered with wire net (2 mm x 2 mm) is fitted at 10 cm height from the bottom of chamber. With suitable modifications, farmers can also convert their tube well chamber into gypsum chamber. Sodic water flowing from below dissolves the gypsum placed in the chamber and reclaims it (Sharma, 2004). Regardless of the method of application, the basis for calculating the gypsum requirement remains the same. However, time of application varies with the method adopted. In case of soil application, the full amount of gypsum is applied as single basal dose. In the case of water-applied gypsum, neutralization takes place before its application and there is, therefore, no build-up of sodicity in the soil (Tyagi, 2003). Water flowing through gypsum-beds picks Ca^{2+} (3-5 meq L^{-1}) and thus becomes far less harmful than original Na^+ saturated water. In fact, soil texture, crop sequence and amount of annual rainfall are the critical factors determining soils' susceptibility to RSC level in irrigation water. In areas having relatively higher annual rainfall (500-600 mm), the upper safe limit of RSC can be as low as 2.5 meq L^{-1} in heavy (fine) textured soils, between 5-7.5 meq L^{-1} in moderately textured and as high as 10 meq L^{-1} in coarse soils; especially when low water requiring crops are grown (Minhas and Tyagi, 1998).

Alternative amendments: Because gypsum is only sparingly soluble in water (2.5 g L^{-1}), large volumes of water are required to hasten gypsum dissolution. Given poor permeability of sodic soils, leaching of displaced Na^+ also takes considerable time. Owing to its high solubility in water, $CaCl_2$ can be a good (direct) source of soluble calcium. After application, $CaCl_2$ works in a manner similar to gypsum but shortens the time required for reclamation. Moreover, in contrast to gypsum and sulphur applied on soil, $CaCl_2$ may be added directly into irrigation water for quick results. In order to give best results, sulphur and similar products should undergo complete oxidation after application. However, high pH of sodic soils limits their oxidation resulting in reduced reclamation efficiency. Complete oxidation of sulphur produces sulphuric acid to replace the exchangeable Na^+. It is due to this reason that sulphur fails to give results comparable to gypsum or sulphuric acid even when used in chemically equivalent quantities (Abrol *et al*. 1988). Recently, an experiment has been started to improve the efficacy of 'Reliance Formulate Sulphur' by circumventing the problems of slow oxidation, dustiness and fire hazard that limit the potential use of elemental sulphur. Efforts are also underway to assess the feasibility of marine gypsum as a substitute for mined gypsum. Marine gypsum, a by-product from the manufacturing process of common salt (NaCl), contains NaCl, $MgCl_2$and $MgSO_4$ as impurities that may increase the ionic strength of aqueous solution by decreasing its activity coefficient resulting in increased solubility of gypsum and higher reclamation efficiency compared to the mineral gypsum. Laboratory experiments revealed very high calcium content (30.5 meq L^{-1}) in marine gypsum based formulation that is in fact comparable to the pure analytical grade gypsum (ICAR-CSSRI, 2017a).

Industrial by-products: Several industrial by-products have also been found effective in overcoming structural and nutritional constraints in sodic soils. Phosphogypsum (hydrated $CaSO_4$), an acidic by-product of wet-acid production of phosphoric acid, is rich in S and Ca. Studies have shown that it can be used as a substitute to mined gypsum and lime for alleviating acidity, Al toxicity, low nutrient availability and sodicity problems. Post methanation effluent (PME) generated through biomethanation of distillery effluent, that is often inadvertently discharged into rivers and other surface bodies, can also be a potential amendment. Fly ash is a by-product of thermal power plants. In India, ≈50% of the produce is utilized by cement and concrete industries. Problems being encountered in the safe disposal of this environmental waste can partly be resolved by utilizing it in sodic soil reclamation. Although fly ash treated soils exhibit marked improvements in soil texture, fertility and water-holding capacity, it can sometimes raise the soil pH, salinity and heavy metal contents. Press mud is a by-product of sugar mills. It contains appreciable quantities of many plant nutrients.

Organic materials: Organic amendments like mulches and composts also improve the cation exchange capacity, water retention and plant nutrient availability in saline and sodic soils. Use of crop residues as mulch increases soil organic carbon, formation of water-stable aggregates and water retention. Mulching also reduces rain drop impact insulating the soil against run-off induced erosion. Mulched soils are less affected by scorching heat resulting in reduced evaporative loss of water and low salt movements to the surface. Straw mulching prevented salt accumulation in brackish water irrigated wheat-summer maize rotation (Pang *et al*., 2010). Saline-sodic soils having permanent cover of tephra mulch became normal after 20 years of experimentation as evidenced by decrease in soil EC_e from 43 to 1.5 dS m^{-1} and ESP from 44 to 9 (Tejedor *et al*., 2003).

Incorporation of municipal solid waste compost (MSWC) accelerates the dissolution of precipitated $CaCO_3$ resulting in increased availability of soluble Ca^{2+} and eventual replacement of Na^+ ions from exchange sites. It is seen that combined applications of gypsum and MSWC can be more effective than their sole applications. MSWC application enhanced the activities of dehydrogenase, alkaline phosphatise and urease enzymes, improved microbial biomass carbon and nutrient availability in a saline-sodic soil (EC_e: 7.2 dS m^{-1} and pH: 8.4) under mustard-pearl millet rotation (Meena *et al*. 2016). Application of MSWC (10 t ha^{-1}) along with gypsum GR_{25} reduced soil pH resulting in enhanced supply of N and P in a saline-sodic soil (pH_2: 10.16; EC_2: 3.09 dS m^{-1}; ESP: 77.5) compared to sole gypsum application (GR_{50}) (Sundha *et al*., 2017).

Engineered nanoparticles: Engineered nanoparticles (ENPs) are increasingly being used for the amelioration of SAS. ENPs currently used for different soil applications can be classified into: metal ENPs (*e.g*., elemental Ag and Fe), fullerenes (Buckminster fullerenes and nanocones), metal oxides (TiO_2, CuO and FeO_2), complex compounds (Co-Zn-Fe oxide), polymer coated quantum dots (cadmium-selenide and polystyrene) (Dinesh *et al*. 2012). Available evidence suggests that ENPs decrease surface run-off and structural anomalies in sodic soils by improving the aggregate stability and IR. Application of polyacrylamide (PAM) (10 ppm) increased water movement throughout the root zone and decreased $CaCO_3$ concentrations in the top 45 cm layer by enhancing calcite solublization. These effects led to Na^+ leaching, reduced soil EC_e and SAR. Soil pH, bulk density and $CaCO_3$ content decreased while saturated hydraulic conductivity increased from 0.05 mm d^{-1} to 40.01 mm d^{-1} in a highly dispersed hard saline-sodic soil treated with polymeric aluminum ferric sulfate (PAFS). Soil ESP and EC_e also decreased by 63.23% and 45.61%, respectively, in 0-8 cm layer and by 34.57% and 37.47%, respectively, in 8-16 cm layer. Rice yields with PAFS application in the first year of cultivation were as high as 4.66 t ha^{-1} compared to only 0.83 t ha^{-1} in control treatment (Luo *et al*. 2015). Ghodsi *et al*. (2015) found that combined application of urban solid waste compost coated sulfur (15 t ha^{-1}) and nano iron oxide powder (20 mg kg^{-1}) decreased the pH and SAR of a saline-sodic soil resulting in increased availability of nutrients to sunflower plants. Solitary applications of both the amendments marginally increased soil EC_e. Kumar and Thiyageshwari (2018) compared the effects of nano-gypsum and mined gypsum at 4 levels of GR (25, 50, 75 and 100%). Application of nano-gypsum 100% GR was very effective in reducing soil pH and ESP compared to mined gypsum at varying levels.

Wang *et al*. (2011) compared 17 different soil conditioners for their ability to promote seed germination and plant growth under saline conditions. Of the tested compounds, addition of Hydrolyzed Polymaleic Anhydride (HPMA) significantly increased germination percentage and plant growth rate in saline-sodic soils by decreasing soil pH, EC and bulk density and increasing clay flocculation and water infiltration rate. HPMA increased $CaCO_3$ to release Ca^{2+} in soil solution to remove the excess Na^+.

Microbial bioformulations: Different microorganisms display higher salt tolerance and can efficiently alleviate salt stress when applied in appropriate form and at right time. Such microbial strains lessen salinity and sodicity risks by reducing the soil pH, EC_e and ESP coupled with improvements in water permeability, soil aggregation, soil microbial biomass carbon and nutrient availability; especially in moderately salt-affected soils. Despite proven efficacy in improving root zone conditions in saline/sodic soils, commercial applications of such microbial inoculants is hampered by relatively higher costs and lack of technical know-how. Concerted efforts to overcome these problems have led to the development of different low-cost microbial bio-formulations capable of improving crop production in salt-affected soils. For example, 'CSR-BIO'- a bioformulations based on consortia of *Bacillus pumilus*, *Bacillus thuringenesis* and *Trichoderma harzianum* on dynamic media, acts as a soil conditioner and nutrient mobilize and increases the productivity of rice, banana, vegetables and gladiolus in sodic soils. Similarly, liquid bioformulations based on halophilic plant growth promoting (HPGP) strains, *viz*., Halo-Azo, Halo-PSB and Halo-Azsp have been commercialized for improving crop yields as well as to improve the fertility of sodic soils. Other formulations like Halo-Rhizo and Halo-Mix are in testing and carrier standardization phase (ICAR-CSSRI, 2017a).

Reclamation and Management of Waterlogged Saline Lands

Sub-surface Drainage Technology: Sub-surface drainage (SSD) is an efficient technique for tiding over the twin problems of waterlogging and salinity. SSD network, consisting of concrete/PVC pipes and filters installed at a specified distance and depth manually or mechanically below the land surface, drains out excess salty water. Gradual improvements in design and drain spacing have enhanced the acceptability of SSD at farmers' fields in several waterlogged saline areas of the country (Gupta, 2015). Initial success of SSD projects in Haryana proved catalytic to its spread in other affected states like Rajasthan, Gujarat, Punjab and Maharashtra where ≈110,000 ha of waterlogged saline area has been ameliorated until now. Reclaimed lands exhibit marked improvements in crop yields (45% in paddy, 111% in wheat and 215% in cotton) and cropping intensity (> 40%) leading to 2-3 fold increase in farmers' income. Depending on factors such as depth and spacing, soil type and topography, SSD cost varies from location to location. The estimated cost at 2015 price level is INR 65,000 ha^{-1} under government funded schemes for alluvial soils of Haryana and INR 1,25,000 ha^{-1} for heavy textured soils (Vertisols) of peninsular India (Sharma *et al*., 2016a).

Impact evaluation studies reveal that active participation of the farmers is critical to the success of SSD technology. At three SSD sites of Jagsi (Sonipat; 430 ha), Siwana Mal (Jind; 295 ha) and Mokhra Kheri (Rohtak; 520 ha) in Haryana, large patches of salinity gradually disappeared due to timely pumping of sump well during the monsoon season. Rice and wheat yields at Jagsi were at par with the yields obtained in normal soils of Haryana. Similarly, rice and wheat yields improved by 35-110 % and 25-120%, respectively, in the selected SSD blocks of Siwana Mal and Mokhra Kheri sites. Saline drainage water was also reused for irrigating rice and wheat crops in some blocks. In Dudhgaon village of Sangali district of Maharashtra, SSD has been installed over ≈1000 ha area benefitting ≈1300 farmers. After SSD implementation, over twofold increase was noted in the average yields of sugarcane, wheat and soybean; apparently due to lowering of watertable and salt leaching. SSD installation has turned the fortunes of farmers in salinity affected Ugar Budruk village of Belgaum District, Karnataka. This project covers ≈925 ha area benefitting ≈650 farmers. Cropping intensity increased from 62.64% (pre-SSD) to 77.62% (post-SSD) due to decline in mean soil salinity from 6.6 to 2.5 dS m^{-1}. Similarly, B: C ratio increased from 0.54 to 1.21 in the ameliorated lands (ICAR-CSSRI, 2017a).

Despite considerable improvements in soil quality, crop yields and farmers' incomes, SSD technology has not spread at the desired pace. Some factors hindering the widespread adoption of SSD include relatively higher initial costs, difficulties in operation and maintenance, lack of active community participation and the problems in safe disposal of drainage water. Small and marginal landholders, though fully aware of the benefits of SSD, can hardly afford the higher establishment costs and recurring expenses. In most of the saline areas of India, water users' associations for drainage and irrigation projects are almost non-existent. Since the success of SSD projects rests on collective responsibility, appropriate institutional arrangements for farmers' participation are needed. Problems in the safe disposal of saline effluents can largely be overcome by adopting saline aquaculture and reuse of saline drainage water in irrigation and soil reclamation.

Land shaping models: Large patches of waterlogged sodic lands occur in canal irrigated areas of IGP where post-monsoon water inundation often adversely affects wheat crop. Waterlogging and secondary sodicity problems have considerably increased in the Sarda Sahayak Canal command area of Uttar Pradesh in the past two decades. The situation is particularly grim in poorly drained sodic water irrigated areas. Notwithstanding the astonishing success of gypsum-based technology in Uttar Pradesh, it has become clear that gypsum application is of little avail in waterlogged sodic lands (watertable < 2.0 m) that constitute ≈15% of the total sodicity-affected area of the state. Watertable rise due to excessive canal seepage increases the translocation of basic salts in the root zone.

Considering such constraints, a need has long been felt to develop a sustainable technology for the management of waterlogged sodic soils. Inversion of low pH deeper soil profiles upside down in a pre-specified soil column by elevating field bed can make soil surface favourable for crop production by lowering the watertable below a critical level to improve the internal drainage. Land modification (fish ponds and raised and sunken beds) based integrated farming models have been tested and validated as a sustainable solution to enhance the economic value of waterlogged sodic soils (pH ≈10.0) for decades (ICAR-CSSRI, 2017a). In sunken beds, watertable lies at ≈1 m depth resulting in reduced upward salt translocation. Cultivation of rice and water chestnut, and integrated rice-fish culture are the economically viable land use options for the sunken beds. Vegetable crops should preferably be grown on raised beds for higher returns (Verma *et al*., 2015).

South-western part of Punjab is also severely affected by these problems. Besides biodrainage and conjunctive use of canal and low quality groundwater, a new technology called multiple well points system is now being recommended to ensure skimming of freshwater floating over brackish groundwater. About 41,000 such wells installed in Muktsar, Faridkot and Ferozepur districts have lowered the watertable by 1-7 m leading to 10-20% increase in crop yields. The cost of installation of a 4-well point system is ≈ INR 45000 per unit (Gupta and Singh, 2014).

Farm ponds are created by excavating ≈20% of the soil from a depth of ≈3 m. Rainwater stored in these ponds can be used for round-the-year irrigation of crops grown on embankments. Besides fish rearing in the pond and crop cultivation on dykes, poultry and duckery can also be taken up for enhancing profits while recycling the resources among different components. In paddy-cum-fish model, trenches (3 m top width × 1.5 m bottom width × 1.5 m depth) are made around the farmland. Excavated soil is used for making dykes (1.5 m top width × 1.5 m height × 3 m bottom width) to prevent free flow of water from the field and harvesting more rainwater in the field and trench. While dykes are used to grow vegetables throughout the year, rest of the farm area including trenches is used for integrated rice-fish culture (Mandal *et al*. 2013). These interventions can increase the cropping intensity from 114% to 186%. These techniques have been demonstrated at farmers' fields for increasing the farm incomes. Subsequent to the adoption of land shaping interventions, farmers' net income could increase from mere INR 470 month^{-1} (*kharif* rice) to as high as INR 11999 month^{-1} (rice-fish-vegetable cropping system). Betel vine cultivation has also emerged as an attractive option to further increase the farm incomes (Mandal *et al*., 2017).

Agro-forestry Models for Sodic Soils

Several trees species slowly improve the physical, chemical and biological properties of sodic soils. Singh *et al*. (1989a) observed that mesquite (*Prosopis juliflora*) trees planted in a sodic soil (pH: 10.4, ESP: 90) showed considerable improvement in growth and biomass production upon gypsum addition compared to control trees indicating that gypsum application may be advantageous in situations where initial soil pH and ESP are too high to suppress the tree growth. Soil pH and salt content decreased while SOC and NPK contents improved with tree age; obviously due to litter fall and rhizospheric depositions. Although intercropping of Karnal grass reduced biomass production in mesquite; improvements in soil properties were faster and greater in mixed system than sole mesquite stand. Kaur *et al*. (2000) found that microbial biomass carbon, SOC, inorganic N and N mineralization rates were much higher in *Acacia*, *Eucalyptus* and *Populus*-based agri-silvicultural systems than both single species stands and rice-barseem rotation in a sodic soil. Soil carbon increased by 11-52% in integrated tree-crop systems. Singh *et al*. (2011) noticed that *Prosopis juliflora, Acacia nilotica* and *Casuarina equisetifolia* plantations significantly reduced soil pH, EC, ESP, and increased SOC and available NPK than control soil (pH_2: 8.8-10.5, ESP: 85-92). Some studies also hint that cultivation of Karnal grass, with or without gypsum application, leads to steady reductions in pH and ESP of degraded sodic soils that seems attributable to *in situ* biomass decomposition and root-mediated improvements in soil quality (Batra *et al*. 1997; Kumar *et al*. 1994). Aromatic grasses like palmarosa (*Cymbopogon martinii*) and lemon grass (*C. flexuosus*) also exerts ameliorative effects in sodic soils without any appreciable reduction in essential oil yield (Dagar *et al*., 2004).

Considering relatively less returns from agro-forestry trees, efforts have been made for raising more profitable fruit crops in sodic lands. Dagar *et al*. (2001) evaluated 10 different fruit species in a highly sodic soil (pH: 10) using auger-hole and pit methods of planting and 5-20 kg of gypsum as amendment. Based on long-term observations, Indian jujube (*Ziziphus mauritiana*), jamun (*Syzygium cuminii*), guava (*Psidium guajava*), aonla (*Emblica officinalis*) and karonda (*Carissa congesta*) were found the promising fruit species for such soils.

Biodrainage in Irrigated Lands

In bio-drainage (*i.e*., biological drainage), salt tolerant trees having higher transpiration rate are planted to arrest salinity build-up in irrigated lands. It is, however, pertinent to mention that bio-drainage is essentially a preventive measure and trees provide best results when planted in the beginning. Some of the suitable tree species found effective in bio-pumping of salty water are eucalyptus, popular and bamboo (Heuperman *et al*. 2002). Besides irrigated areas, planting of perennial trees and shrubs can also arrest the rise of saline groundwater in dryland areas. Nonetheless, shallow saline watertables in discharge zones often hinder such revegetation plans. Even if revegetation is successful, the maximum reduction in watertable depth in discharge areas is ≈2.5 m suggesting the practical utility of bio-drainage for localized salinity management in recharge areas (George *et al*. 1999). While the roots of annual crops mostly remain confined to upper few centimetres of the soil, tree roots extend to greater depths (>2 m) and rapidly transpire the groundwater such that watertable may decrease by 1-2 m over a period of 3-5 years. Many tree species have dimorphic roots consisting of surface and sinker components. While surface roots have a horizontal spread, sinker roots penetrate vertically to 10 m depth or more. Together, they form an integrated conduit in the soil that causes upward hydraulic redistribution of the deep soil water (Devi *et al*., 2016).

Although precise quantitative information on biodrainage potential of different tree species is lacking, *Eucalyptus* has emerged as the tree of choice under Indian conditions. *Eucalyptus* trees of 3-4 y ages can bio-drain over 5000 mm of water from non-saline, moderately deep (≈1.5 m) watertables. Relatively shallow (≈1 m) or deep (≈ 2 m) watertable depths reduce the trees' bio-drainage capacity that also declines with increase in the salinity of groundwater. However, at salinities as high as 12 dS m^{-1}, *Eucalyptus* trees can remove ≈50% of the water compared to that under non-saline conditions. *Eucalyptus tereticornis* trees could control watertable rises up to 1.95, 3.48, 3.76 and 3.64 m in first, second, third and fourth years of planting, respectively. After tree planting, salinity up to 45 cm depth did not exceed 4 dS m^{-1} even at saline (12 dS m^{-1}) watertable depth of 1 m. Similarly, bamboo (*Bambusa arundinacea*) plants could control watertable rises up to 1.09, 1.86, 2.46 and 2.96 m in first, second, third and fourth years of growth, respectively (Chhabra and Thakur, 1998). Strip plantations of *Eucalyptus tereticornis* on ridges in north-south direction not only lowered the watertable by 0.85 m in 3 years but also sequestered 15.5 t ha^{-1} carbon during the first rotation of 64 months. B: C ratio of the first rotation of strip-plantations was 3.5: 1. Wheat yield in the tree interspace was over threefold higher than in adjacent waterlogged soils (Ram *et al*. 2011). These observations suggest that trees capable of extracting saline water from deeper layers can control watertable rise in irrigated commands to prevent the formation of waterlogged saline lands.

Salt Tolerant Cultivars

Genetic improvement programmes have led to the development of several salt tolerant cultivars (STCs) in staple crops like rice and wheat that are being cultivated over a large salt-affected area. Seven salt toleraant varieties of rice CSR 10, CSR 13, CSR 23, CSR 27, Basmati CSR 30, CSR 36, CSR 43, five varieties of wheat KRL 1-4, KRL 19, KRL 210, KRL 213 and KRL 283, five of Indian mustard CS 52, CS 54, CS 56, CS 58 and CS 60 and one in chickpea Karnal Chana 1 have been released by CVRC for affected areas of the country. Three rice varieties have also been released for coastal region as Sumati, Bhutnath and Amal mana. Several potential genetic stocks have also been developed for the use as parents in future selection and hybridization programmes. Importance of high yielding STCs is best illustrated by rice, a salt-sensitive plant inefficient in controlling the influx of Na^{+} through the roots, where high yielding STCs can provide a yield advantage of 1.5-2 t ha^{-1}. Many promising salt tolerant genotypes have also been identified in fruits (mango, bael, ber, guava and pomegranate) and vegetables (chilli, capsicum, okra and tomato). Technique for utilizing saline groundwater (EC_{IW} up to 10 dS m^{-1}) in vegetables crops under low-cost protected structure has been standardized. A germplasm repository consisting of diverse medicinal and aromatic plants has been established in a partially reclaimed sodic land. Success has also been achieved in raising fruits like guava, bael, Indian jujube and pomegranate under saline shallow watertable conditions that are otherwise considered to be unsuitable even for field crops.

Of late, molecular and genomic tools are increasingly being employed to understand the biochemical and molecular basis of salt tolerance in different crops. Identification of such traits can pave the way for their introgression in popular (but salt sensitive) cultivars through conventional and marker-assisted breeding approaches. Ravikiran *et al*. (2017) screened 13 SSR markers associated with *Saltol* region on chromosome 1 in 192 rice genotypes. Based on polymorphism and genetic diversity indices, markers RM 493 and RM 10793 were found to be highly useful for distinguishing genotypes.

Technologies for Sustainable Intensification in Reclaimed Lands

Besides rising threat of secondary salinization, repeated instances of resodification and resalinization of reclaimed lands have set alarm bells ringing in many areas. Reversion of reclaimed lands to the pre-reclamation state implies that efforts made for reviving the soil productivity were in vain. Resodification refers to the reappearance of sodic patches in a sizeable area of reclaimed sodic soils. In Etawah district of Uttar

Pradesh, out of total (3,905 ha) reclaimed sodic area, nearly one fourth had relapsed showing the signs of degradation (Yadav *et al*. 2010). It appears that lands in immediate vicinity of canals; especially those suffering from problems of hard sub-soil pan, drainage congestion and shallow watertable, are extremely susceptible to resodification. Similarly, resalinization of ameliorated saline lands can be ascribed to climate- and human-induced redistribution of salts to the surface soil. In both the cases, poor on-farm water management seems to accentuate the extent of salt build-up. Available evidence also suggests that indiscriminate irrigation and agro-chemical use have led to many second generation problems such as groundwater depletion and contamination, loss of soil organic carbon and nutrients, pest and disease outbreaks and crop residue burning in several parts of RWCS covering nearly 12 M ha area in India. These problems together with stagnant and/or declining crop yields have wide ranging ramifications for the food, environmental and economic security of the country. Several options are available to contain these problems.

Integrated farming: An integrated crop-fish-livestock model has been standardized for the small landholders (2 ha land area) of reclaimed sodic areas. This model consists of field and horticultural crops, fish culture, cattle, poultry and beekeeping. Available resources can efficiently be recycled among different components for reducing the environmental foot prints and lessening the production costs. Integration of different components ensures higher and regular incomes to the farm families who otherwise derive incomes from rice and wheat crops only. Generation of round-the-year employment and nutritional security of farm families are the added benefits of this model (Sharma and Singh, 2015).

Adoption of conservation agriculture: Conservation agriculture (CA) practices coupled with the replacement of rice with low water requiring crops like maize may be helpful in achieving sustainable crop intensification in IGP of India. Gathala *et al*. (2014) compared four cropping system scenarios including the farmers' practice and found that resource conservation technologies such as reduced tillage, residue management, crop substitution and innovative crop establishment methods efficiently enhanced the system productivity and profitability. Direct-seeded rice with residue retention provided equivalent or higher yield with 30-50% saving in irrigation water use than farmers' practice of puddled transplanted rice. Replacement of rice with zero-tillage maize gave similar profits while saving ~90% irrigation water. Choudhary *et al*. (2018) observed that CA-based sustainable intensification of maize-wheat systems was a better alternative to RWCS as it could save 79% of precious water while enhancing crop and water productivity by 12 and 145%, respectively along with high (34%) economic benefits. Tirol-Padre *et al*. (2016) found that switching from conventional to CA-based practices in rice crop can reduce global warming potential (GWP) for rice by 23% or by 1.26 Tg CO_2 eq y^{-1}. An intensive CA-based rice-wheat and maize-wheat system reduced GWP by 16-26% or by 1.3-2.0 Tg CO_2 eq y^{-1} compared with the conventional rice-wheat system mainly due to reduction in diesel and electricity consumption.

Carbon Sequestration: Soil organic carbon (SOC) pool is an important measure of soil health. Salt-affected lands generally have very low SOC stock that can be explained by the virtual absence of vegetation cover and, consequently no organic carbon input to the soil. In sodic soils, clay dispersion increases SOC mineralization. Saline conditions can hasten organic matter decomposition but flocculation of aggregates due to high salinity often restricts access to substrates for microbial respiration. Presence of carbonates may further complicate the carbon dynamics (Wong *et al*. 2010). Low SOC stock, in turn, results in lower levels of soil microbial biomass (SMB) and microbial respiration rates. Addition of organic material activates the salt tolerant microorganisms that otherwise remain dormant in salt-affected soils. Organic material (kangaroo grass; 10 t ha^{-1}) treated acidic and alkaline saline-sodic soils had the highest levels of SMB and soil respiration while their lowest levels were noted in untreated (control) soils (Wong *et al*. 2009). A laboratory incubation experiment conducted on non-salt-affected and salt-affected soils from India and Australia showed that EC was the main factor influencing soil respiration. Particulate organic carbon, humus-C and clay were also found to influence soil respiration with the degree of influence depending on whether the soils were salt affected or not. Cumulative CO_2-C emission was negatively correlated with EC in saline soils from both regions. SAR was negatively related with cumulative CO_2-C emission only for the unamended saline-sodic soils of Australia (Setia *et al*., 2011).

A study conducted in China revealed that in croplands converted into tree plantations, secondary forests and grasslands SOC stock built up at an average rate of 36·67 $g\ m^{-2}\ y^{-1}$ in the top 20 cm layer; albeit with large variation. After land use change, SOC stocks decreased during the initial 4-5 years, followed by an increase after above ground vegetation restoration (Zhang *et al*. 2010). Several studies conducted in India have also shown that revegetation of SAS with trees/grasses raises their SOC level. Soil organic matter, total carbon storage and biological productivity were much higher in the silvipastoral system consisting of trees (*Acacia nilotica*, *Dalbergia sissoo* and *Prosopis juliflora*) and grasses (*Desmostachya bipinnata* and *Sporobolus marginatus*) compared to sole grass blocks in a highly sodic soil (Kaur *et al*. 2002). SOC storage up to 1 m depth over a period of 15 years was 16.7-24.7 t C ha^{-1} in a natural grassland ecosystem in sodic soils (pH: 8.0-10.2). Integration of trees with grasses further enhanced carbon storage by 15-57 %. It has been found that rice-*Eucalyptus camaldulensis* system can sequester 24 t CO_2-eq. ha^{-1} on moderately saline soils in coastal Bangladesh over the plantation lifetime. Similarly, rice-wheat- *Eucalyptus tereticornis* and *Acacia nilotica* plantations on saline-sodic soils of Haryana (India) and Punjab (Pakistan) can sequester 6 and 96 t CO_2-eq. ha^{-1}, respectively, over plantation life time (Wicke *et al*., 2013). Among different land use systems, *viz*., fruit trees (guava, litchi, mango, jamun), agro-forestry systems (*Eucalyptus tereticornis* and *Prosopis alba*) and RWCS system in a partially reclaimed sodic soil of north-western India, guava land use exhibited the highest SOC storage (133 Mg C ha^{-1}) as well as the maximum passive C pool (76 Mg C ha^{-1}) due to decomposition of leaf litter and subsequent deposition in the root zone over the years (Datta *et al*., 2015).

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