

Salinity Research in India- Achievements, Challenges and Future Prospects

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ABSTRACT

Salinity is one of the major constraints in sustainable food production in many parts of the world. In a changing global scenario characterized by extreme climate variability, land and water degradation, biodiversity loss and trade regulations, the food and nutritional security of a burgeoning population is a cause for concern to the researchers and policy makers. As day-to-day increasing competition for productive lands and fresh water resources coupled with pervasive land use are pushing agriculture to the marginal environments, ensuring sustainable agricultural productivity and remunerative returns to the growers remain the major challenges. Since its establishment, ICAR-Central Soil Salinity Research Institute, Karnal has made significant contributions in harnessing the productivity of salt-affected soils and waters. In spite of credible achievements in the reclamation and management of saline and sodic soils for crop production, different soil, climatic, anthropogenic and policy constraints continue to hinder the productive utilization of vast saline tracts lying in arid, semi-arid and coastal regions of the country. After reviewing the current global trends, we proceed to scrutinize our strengths and weaknesses in salinity management in agriculture with a view to present a plausible future course of action while taking into account the present and emerging challenges.

Key words: Land degradation, reclamation, salt-affected soils, sustainable production.

1. INTRODUCTION

Worldwide prevalence of hunger and malnutrition, depleting energy reserves and severe deterioration in environmental health- often collectively referred to as 'Three Furies'- are increasingly seen as big threats to the sustainable human living (Escobar *et al.*, 2009). The 2015 issue of *The State of Food Insecurity in the World* paints a grim picture of global food and nutrition security with a large chunk of population in many regions of Asia, Africa and Latin America suffering from chronic undernourishment. Although some of the Asian regions such as East and Central Asia have made remarkable progress in the last two decades, the number of undernourished people remains quite high in most parts of South Asia and India still has the second highest estimated number of undernourished people in the world (FAO, IFAD & WFP, 2015). While technological improvements in agriculture have dramatically increased food production in the past few decades (Godfray *et al.*, 2010), the recent fears of food insecurity triggered, *inter alia*, by land and environmental degradation (Pimentel, 2006), climate change (Godfray *et al.*, 2010), diversion of arable lands for biofuel production (Escobar *et al.*, 2009) and increase in global

food prices (Godfray & Robinson, 2015) could potentially dilute the prospects of a food secure world.

Given the fact that over 99.7% of the globally consumed food is produced in terrestrial ecosystems, while the remainder 0.3% comes from oceans and other aquatic systems (Pimentel, 2006), sustaining soil health and productivity will be crucial to ensure sufficient, secure and sustainable access to food to an ever increasing population. The growing realization that climate change would adversely affect global food output adds to the worry of the majority of developing countries as they are likely to be worst affected by the climate change induced food scarcity and hunger risks (Parry *et al.*, 1999; Godfray *et al.*, 2010). The rapidly increasing use of biofuels derived from food crops such as sugarcane and maize may further accentuate the problem of food insecurity. The United States, for example, presently accounts for over 70% of global maize exports and the soaring number of bio-ethanol production distilleries in this country could distort the global maize trade resulting in drastically reduced maize supplies to many developing countries (Escobar *et al.*, 2009). Many intersecting challenges such as poverty and social inequality (Smith *et al.*, 2000), land use change (Godfray

et al., 2010), soil erosion (Pimentel, 2006), biodiversity loss (Tscharntke *et al.*, 2012), fresh water scarcity (Rijsberman, 2006), huge food wastage (Parfitt *et al.*, 2010) and dietary transition (Rijsberman, 2006; Godfray *et al.*, 2010) also come into picture in discussions on food security.

Across the world, many undesirable anthropogenic activities (e.g., deforestation and intensive cropping) have caused severe harm to agro-ecosystem health, carbon and hydrological cycle and floral-faunal diversity which are vital to a sustainable future (Foley *et al.*, 2005; Lotze-Campen *et al.*, 2008). Soil erosion, as an environmental constraint, severely limits the productivity of agricultural lands. Globally, about 75 billion tonnes of annual soil loss, primarily from the agricultural landscapes, is attributed to erosion. In some regions of Asia, Africa and South America, annual soil loss due to erosion is as high as 40 t ha⁻¹ yr⁻¹. In India, land degradation due to soil erosion affects over 40% (150 m ha) of the total geographical area (Dabral *et al.*, 2008). Soils in arid regions characterized by poor organic matter availability and low fertility are more prone to erosion induced loss of top fertile layers (Bhatt & Khera, 2006). As United Nations has declared the present decade (2011-2020) as the 'Decade of Biodiversity', the debate that agricultural intensification for augmenting food production should not come at the cost of biodiversity erosion has acquired a new dimension (Tscharntke *et al.*, 2012) and the proponents of 'sustainable intensification in agriculture' are in favour of environmental-friendly agricultural intensification interventions to enhance crop yields while significantly eliminating the chances of land degradation and greenhouse gas emissions (Garnett *et al.*, 2013; Tilman *et al.*, 2011).

An enormous amount of food produced goes waste in the food supply chain. According to one estimate, about half of all food produced is lost before and after it reaches the consumer (Lundqvist *et al.*, 2008). The heavy environmental footprint of food wastages, in terms of huge loss of water and nutrient inputs and the higher greenhouse gas emissions (Parfitt *et al.*, 2010) are seen as unintended side-effects of the loopholes in global food production and supply chain. Thousands of litres of water are required to produce the daily per capita food requirements. The exact amount of water used to produce a given amount of food (calorie requirements) varies with the region (Xu & Singh, 2005) and the type of food consumed (Rijsberman, 2006). In California, for example, production of one kilogram beef may require much more water than producing one kilogram of cereals (Rijsberman, 2006). With a dietary transition underway due higher purchasing power, significant increase in consumption of processed food and dairy products, meat and fish is evident which is bound to further increase the pressure on food production systems (Godfray *et al.*, 2010) and may substantially increase their ecological footprint largely because of enhanced use of water and agro-chemicals in food production, processing and transport (Rijsberman, 2006; Godfray *et al.*, 2010).

The foregoing account of diverse challenges impacting global food production and supply chain compels us to explore the sustainable ways and means to ensure the food and nutritional needs of an increasing world population. While searching the alternatives, we have to consider the facts that productive agricultural lands are limited; the natural resources are degraded and overstretched; energy and water constraints are becoming serious with each passing day and that emerging challenges such as climate change may present formidable stumbling blocks in realizing the goals of sustainable agricultural development. The purpose of this paper is to briefly discuss the need for and prospects of sustainable crop production in saline environments while ensuring the sustainability in all its dimensions-social, economic and environmental.

2. NEED TO HARNESS THE PRODUCTIVITY OF SALT-AFFECTED SOILS

The business-as-usual approach, based on the use of improved seeds, liberal irrigation and heavy use of agro-chemicals, adopted to enhance the agricultural production in Green Revolution period may no longer work in a changing scenario characterized by limitations such as diversion of agricultural lands for other uses (Lotze-Campen *et al.*, 2008), unabated land degradation (Oldeman, 1998), water scarcity (Lotze-Campen *et al.*, 2008), and climate change induced risks (Rosenzweig *et al.*, 2004) which are adversely impacting agriculture in many parts of the world. In spite of substantial increase in global food production, Green Revolution lacked the concerns for social and environmental sustainability (Conway and Barbie, 1988; Sinha, 1997). Forty years down the line, there is a growing realization that intensive water and energy use driven agricultural development strategy pursued since 1960s resulted in huge damages to soil productivity, water quality, biodiversity and environmental sustainability (Singh, 2000). The productivity gains, primarily attributed to large increases in crop production, were also uneven across the crops and regions (Evenson and Gollin, 2003).

The current state of competition for land use from housing, bio-energy and industrial sectors coupled with severe water shortages (Godfray *et al.*, 2010) and the alarming rate of natural resource degradation and biodiversity loss (FAO, 2011) have necessitated a paradigm shift in the conventional ways and means of food production. While continued development and spread of salt-affected soils (SAS) is seen as a threat to agricultural sustainability, these degraded ecosystems offer immense opportunities to harness the productivity potential through appropriate technological interventions. Even marginal to modest gains in crop yields in such soils would mean dramatic improvements in the lives of thousands of poor farmers in salinity affected regions of the world. In this background, our purpose is to highlight the past achievements, current state of research, emerging challenges and future requirements to sustainably utilize the salt affected soil and water resources with special reference to work done in India under the aegis of ICAR-CSSRI.

3. GENESIS, CHARACTERISTICS AND GLOBAL DISTRIBUTION OF SALT-AFFECTED SOILS

Soil reaction (pH_s) and electrical conductivity (EC_e) of soil saturation extract, exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) are the criteria used to classify the salt-affected soils. Based on these parameters, SAS are classified into two main categories: saline and sodic (Abrol *et al.*, 1980). All soils invariably contain soluble salts, but under certain soil and environmental conditions, excess salts accumulate in the root zone which often deteriorate the soil properties- physical, chemical and biological- to such an extent that crop production is adversely affected (Rengasamy, 2006). The excess soluble salts present in saline soils- characterized by EC_e values above 4 dS m^{-1} at 25°C - render them unsuitable to grow majority of the food crops. Similarly, in sodic soils excess exchangeable sodium percentage (ESP; >15) adversely affects the growth and development in most crop plants (Abrol *et al.*, 1988). Besides physical and chemical weathering of rocks and primary minerals as the main processes, other factors responsible for the formation and/or accumulation of soluble salts in soils include irrigation with saline groundwater, development of saline creeps due to excessive leaching, ingress of sea water in coastal regions, congestion of natural drainage and seepage from canals, waterlogging due to faulty irrigation practices and localized redistribution of salts. The chlorides and sulphates of Na^+ , Ca^{2+} and Mg^{2+} are the dominated neutral soluble salts in saline soils. Saline soils have good physical properties and water permeability. White salt crusts on the surface and scattered growth of crops are the indicators of salinity problem (Singh, 2009). High salt concentrations due to ancient marine deposits, poor drainage and shallow water table conditions often tend to accentuate the salinity problem (Horney *et al.*, 2005).

The factors responsible for the formation of sodic soils include alternate wet and dry seasons, groundwater containing carbonates and bicarbonates, desalinization and the reduction of sulphate ions under anaerobic conditions. Majority of the sodic soils in Indo-Gangetic plains seems to have formed due to alternate wet and dry seasons. In wet months, water having products of alumino-silicate weathering accumulated in the low lying areas. In the ensuing dry season, high evaporation induced concentration of soil solution caused an increase in the proportion of sodium ions on the soil exchange complex with simultaneous increase in pH. This process repeated over years resulted in the formation of sodic soils. In these soils, excess exchangeable sodium and high pH result in the dispersion of clay and poor physical properties and restricted water permeability (Abrol *et al.*, 1988; Singh, 2009).

Globally, about 1128 m ha area is affected by salinity and sodicity stresses. The regions with preponderance of salt-

affected soils are Middle East (189 m ha) followed by Australia (169 m ha) and North Africa (144 m ha). South Asia, including India, has about 52 m ha salt-affected area. It is interesting to note that a major chunk of total global area (~85%) is only slightly to moderately affected by high salt concentrations while the remainder 15% suffers from severe to extreme limitations for crop cultivation (Wicke *et al.*, 2011).

In India, the area under salt-affected soils is about 6.73 million ha with states of 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 accounting for almost 75% of saline and sodic soils in the country. In most of the salt-affected environments, prevalence of poor quality (saline and sodic) waters is also noted. The states of Rajasthan, Haryana and Punjab, lying in the north-western arid part of the country, greatly suffer from the problem of marginal quality waters (Singh, 2009). According to estimates, the present area under salt-affected soils (6.73 million ha) in country would almost treble to 20 million ha by 2050 (Sharma *et al.*, 2014a). The problem of poor quality waters would also significantly increase in the foreseeable future due to planned expansion in irrigated area and intensive use of natural resources to fulfil the food and other livelihood requirements of an increasing population (Sharma *et al.*, 2011).

4. EFFECTS AND MECHANISMS OF SALT TOLERANCE IN PLANTS

The plants growing in salt-affected soils exhibit two distinct phases- osmotic (water) stress and salt stress- of growth inhibition (Munns, 1993). The osmotic stress, due to higher water potential in root cells than surrounding soils, prevents water uptake by plant roots resulting in water deficit and a myriad of physiological and biochemical abnormalities then adversely affect their growth (Hauser and Horie, 2010). Under normal conditions, plants exhibit high cytosolic K^+/Na^+ ratio through a mechanism called ion homeostasis which is disrupted under salinity. As Na^+ and K^+ have a similar radius, transport channels in cell membranes fail to distinguish between these two ions. Due to this reason, in saline soils (having higher Na^+ concentration), K^+ transporting channels exhibit excessive uptake of toxic Na^+ ions resulting in the disruption of normal cytosolic ionic balance with detrimental consequences for plant growth (Katiyar-Agarwal *et al.*, 2005). Elevated Na^+ concentrations not only prevent K^+ absorption but also adversely affect the activities of key enzymes involved in important metabolic processes such as photosynthesis and protein synthesis (Hauser and Horie, 2010). Apart from high ESP, nutrient deficiencies and toxicities, major constraints for plant growth in sodic soil stem from their poor physical properties, surface crusting and hardsetting. These problems affect water and air movement, runoff, water holding capacity, plant root penetration, seedling emergence and tillage operations (Murtaza *et al.*, 2006).

The salt stressed plants tend to achieve osmotic equilibrium in the cells through osmotic adjustment which is achieved by accumulation of large quantities of osmolytes comprising of organic solutes and inorganic ions. Organic solutes, also referred to as compatible solutes, include proline, sugars and other low molecular weight metabolites. By accumulating these solutes, plant cells either lower or balance the osmotic potential of intracellular and extracellular components. Inorganic ions (Na^+ , K^+ , Ca^{2+} , and Cl^-) also significantly contribute to osmotic adjustment in different plant species (Chen and Jiang, 2010). To achieve favourable ionic balance under saline conditions, plants either exclude the excess salts (salt exclusion) or compartmentalize the absorbed salts in cell vacuoles (salt compartmentalization). Although most of the salt tolerant plants (halophytes) possess both salt exclusion and compartmentalization traits, their salt sensitive counterparts (glycophytes) are often poor in excluding toxic ions as well as compartmentalizing the absorbed salts. Nonetheless, many glycophytes exhibit moderate to high salt tolerance which is attributed to selective ion uptake in saline soils, preferential accumulation of K^+ in aerial parts and retention of Na^+ in upper root and basal stem tissues (Munns, 2002).

5. MAJOR TECHNOLOGICAL ACCOMPLISHMENTS FOR SUSTAINABLE USE OF SALT-AFFECTED SOILS

ICAR-Central Soil Salinity Research Institute (CSSRI) was established in 1969 to undertake basic and applied researches in the field of salinity management in agriculture. Over the years, the Institute has grown into an internationally recognized research institution of repute (Sharma *et al.*, 2011). Concerted research efforts in the past four decades have resulted in the development of a number of technologies for the reclamation and management of salt affected soils and use of poor quality water for crop production in different agro-ecological zones of the country. The wide adoption of technologies developed by the Institute- gypsum-based sodic soil reclamation, sub-surface drainage of waterlogged saline lands, salt tolerant varieties and improved agro-forestry techniques to name a few- are a shining testimony to its research credentials (Sharma *et al.*, 2014a). A brief account of salinity management technologies developed and their impact on agricultural development in country is presented in the succeeding paragraphs:

Delineation of Salt-affected Soils: Based on the assumption that precise mapping and classification are essential to understand the nature and degree of salinity and sodicity for the reclamation programmes, sustained efforts have been made to develop the reliable estimates of salt-affected soils of India. The availability of many cost-effective and rapid tools such as geographic information system and remote sensing has by and large replaced the tedious and time consuming conventional techniques (based on collection of soil and water samples and their analyses) for the accurate

delineation of salt-affected soils. Remote sensing, often in combination with ground truth observations, provides speedy and accurate information on distribution and extent of SAS (Singh *et al.*, 2010). So far, mapping on 1:250000 scale has been done in 15 salt-affected states of India and efforts are in progress to digitize the maps on 1:50000 scale. By reconciling different estimates, total salt affected area in country has been computed to be 6.73 million ha. Saline and sodic soils constitute about 40% and 60%, respectively of the total salt-affected soils (Sharma *et al.*, 2014a). Availability of information regarding state-wise distribution of saline and sodic soils has been of great help to policy makers and stakeholders in planning and executing the soil reclamation programmes (Singh *et al.*, 2010). In addition, the first approximation water quality map of India has also been published (Sharma *et al.*, 2014a).

Reclamation and Management of Sodic Soils: The fact that about 2.0 million ha of barren sodic soils have been put under crop production is a pointer to the immense popularity of gypsum-based alkali land reclamation technology in the country. The sodic area reclaimed so far is contributing approximately 16-17 million tonnes of paddy and wheat to the national food basket per annum. Farmers obtain higher rice and wheat yields (5 and 3 t ha⁻¹, respectively from 3rd year onwards) in the reclaimed lands. Besides, it has generated on-farm and off-farm employment of over 210 million person-days during the last three decades (Sharma *et al.*, 2014a).

Sodic soil reclamation, which essentially aims to replace the sodium by calcium on exchange sites and the subsequent removal of exchanged sodium by the application of good quality water, is often context-specific and depends on the availability of amendments and the crops to be grown. The amendments used for sodic soil reclamation are broadly grouped into three categories: *soluble calcium salts* such as gypsum and calcium chloride, *acids and acid forming substances* such as sulphuric acid and pyrite, and *calcium salts of low solubility* such as ground limestone. The relative efficacy of a given amendment, its influence on soil properties and crop growth and the costs involved are the guiding principles in use of chemical ameliorants (Abrol *et al.*, 1988). Depending on soil chemistry, calcium may either be applied directly (in the form of gypsum) or indirectly (sulphuric acid, elemental sulphur etc.; Horney *et al.*, 2005). In most of the cases, native calcium carbonate levels (Horney *et al.*, 2005) and soil pH (Abrol *et al.*, 1988) determines the type of chemical amendment to be used. In soils low in carbonate, direct application of calcium (mostly gypsum; lime in low pH soils) is recommended. The sodic soils rich in calcium carbonate may be reclaimed using sulphuric acid which reacts with the native calcium to form gypsum, which then supplies exchangeable calcium. In addition, application of elemental sulphur (which is oxidized by *Thiobacillus* and related bacteria to form sulphuric acid which in turn reacts to form gypsum) may give desirable effects under certain conditions. In a particular location, for example in San

Joaquin Valley of California, the soil chemical conditions may allow the use of different amendments in sodic soil reclamation (Horney *et al.*, 2005). The practical use of ground limestone and lime in sodic soil reclamation is limited by their poor efficiency under high soil pH conditions. As most of the sodic soils possess considerable quantities of sodium carbonate which imparts high soil pH, their reclamation is possible only through the use of soluble calcium salts or acid/acid-forming substances. Similarly, the applications of highly soluble calcium chloride and sulphuric acid are hindered by prohibitive costs and handling difficulties, respectively. Under these constraints, gypsum has emerged as the most preferred chemical amendment for sodic soils due to its relatively easy availability and low cost (Abrol *et al.*, 1988).

Reclamation and Management of Saline Soils: The usefulness of subsurface drainage as an effective technological intervention to overcome the twin problems of waterlogging and salinity is well known (Gupta, 2002). The sub-surface drainage network consists of concrete or PVC pipes along with filters installed manually or mechanically at a particular spacing and depth below the soil surface, and works by draining out the excess water containing soluble salts (Singh, 2009). Although initially developed for Haryana, sub-surface drainage projects have been widely and successfully replicated in other salinity affected states such as Rajasthan, Gujarat, Punjab, Andhra Pradesh, Maharashtra, Madhya Pradesh and Karnataka where about 1,10,000 ha waterlogged saline soils have been reclaimed and put under crop production. The crops grown in the reclaimed saline soils exhibit high to very high increases in yield (45% in paddy, 111% in wheat and 215% in cotton) and cropping intensity (Sharma *et al.*, 2014a).

In spite of tangible socio-economic benefits in terms of on-farm employment generation and productivity gains, the rapid adoption of this technology is hindered by the higher initial establishment costs, operational difficulties, lack of community participation and the problems encountered in disposal of drainage effluents (Singh, 2009). Although farmers are fully aware of the benefits of sub-surface drainage, they could hardly afford the higher costs involved in establishment and maintenance of these systems. In most of the salinity affected regions of the country, water users' organisations for irrigation and drainage projects are almost non-existent. Since the success of subsurface drainage projects rests on collective responsibility, appropriate institutional arrangements for farmers' participation and organisation are required (Ritzema *et al.*, 2008).

Phytoremediation of Salt-affected Soils

Due to high environmental footprint of saline soil reclamation by salt leaching with fresh water and the problems encountered in obtaining and using the costly chemical ameliorants in required amounts to reclaim sodic soils, efforts have been made to identify salt tolerant trees, shrubs and grasses for cost-effective phytoremediation

of these soils without any incurring expenditure in an environmental-friendly manner. Available evidences indicate that difficult to cultivate saline and sodic soils can be made productive by raising tree plantations (Mishra *et al.*, 2003; Qadir *et al.*, 2007). The restoration of degraded saline and sodic soils under tree cover is attributed to gradual improvements in their physico-chemical and biological properties. In most of the cases, tree cover augments the soil organic carbon and nutrient contents and brings out a gradual decrease in exchangeable sodium and soluble salt concentrations. Together, these effects contribute to the productivity enhancement of salt-affected soils (Bhojvaid and Timmer, 1998; Mishra *et al.*, 2003; Nosetto *et al.*, 2007). Under tree cover, the decrease in soil bulk density is often accompanied with an increase in soil porosity, water holding capacity, permeability and water infiltration rate (Mishra *et al.*, 2003). Due to substantial improvements in infiltration rates under tree plantations, soluble salt content significantly decreases in the upper soil layers (Nosetto *et al.*, 2007). The higher microbial biomass pool under tree cover, probably due to organic matter addition through leaf litter, favourably enhances the soil health and productivity (Kaur *et al.*, 2000).

Sustained research efforts at ICAR-CSSRI have culminated into the development of viable agroforestry techniques and agronomic practices which hold high importance for the best productive use of large tracts of salt-affected community and government lands lying barren due to one reason or another. Some of the promising species for sodic soil reclamation include *Prosopis juliflora*, *Acacia nilotica*, *Casuarina equisetifolia*, *Tamarix articulata* and *Leptochloa fusca* (Singh *et al.*, 1994). In waterlogged saline soils, *Prosopis juliflora*, *Tamarix articulata*, *Casuarina glauca*, *Acacia farnesiana*, *A. nilotica*, *A. tortilis*, and *Parkinsonia aculeata* give good results (Dagar & Tomar, 2002). Similarly, *Eucalyptus tereticornis*, *Populus deltoides* and *Tectona grandis* based agroforestry systems are promising for reclaimed salt-affected lands (Singh *et al.*, 1994). Commercial plantations of these agro-forestry trees in salt affected lands could alleviate fuel wood and forage scarcities and may prove useful in sequestering carbon to moderate the impacts of climate change (Sharma *et al.*, 2011).

Site Specific Management Options: The saline and sodic soils often exhibit considerable spatial variations in soluble salt and exchangeable sodium concentrations. This variability results in patchy crop growth and poor yields (Singh *et al.*, 2010). In some cases, inherent spatial variability could be managed by applying site-specific management (SSM) practices which aim at the management of an agricultural crop at a spatial scale smaller as compared to the whole field. The SSM is based on the premise that that microclimate for crop growth varies substantially from one part of the field to another. If these variations can be properly quantified, then management practices may be adjusted to provide appropriate response to conditions at different locations in the field.

A few preliminary studies carried out in the salinity affected Imperial and San Joaquin Valleys of the United States have indicated the potential of this approach in variable rate application of inputs (e.g., fertilizer N) to obtain higher yields while minimizing the input use efficiency (Horney *et al.*, 2005; Kaffka *et al.*, 2005). Some of the constraints which need more emphasis include the efforts to ensure that costs incurred in the procedure should not exceed the value of the saved amendment. Again, in some cases, amendment application on the basis of bulk soil electrical conductivity may result in amendment use in locations where it is not required (Horney *et al.*, 2005).

Technologies for Coastal Saline Soils: A number of technologies have been standardized to sustain crop production in coastal saline soils of the country. 'Dorovu' technology to skim fresh water floating on the saline water has gained immense popularity in many coastal regions. Other such technologies include *rabi* cropping in mono-cropped coastal saline soils, rainwater harvesting in dugout farm ponds, salt tolerant rice varieties (Sumati and Bhootnath), efficient nutrient management and integrated rice-fish culture (Sharma and Chaudhari, 2012).

Technologies for Salt-Affected Vertisols: Salt-affected black soils (vertisols), which occupy about 1.21 million hectare in Gujarat alone, are increasing in Karnataka, Maharashtra and Rajasthan. Due to their high clay content, these soils are adversely affected even at low salt and exchangeable sodium concentrations. Rehabilitating these saline soils is far more cumbersome as compared to alluvial sandy loam soils of Indo-Gangetic Plains. Technologies developed for the commercial cultivation of *Salvadora* (a halophyte which tolerates salinity up to 50 dS m⁻¹), dill (tolerates salinity of 4-6 dS m⁻¹), castor and sunflower have become popular among the farmers (Sharma and Chaudhari, 2012).

Salt Tolerant Varieties: The small and marginal farmers in salt-affected environments could hardly afford the costs involved in chemical amendments-based reclamation technology without government support. Consistent with the need to provide these poor farmers viable and cost-effective solutions to adapt to stressful saline/sodic soils, Institute has identified/developed high yielding salt tolerant varieties in rice, wheat, mustard and other crops. These varieties exhibit tolerance to salinity and high soil pH and give significantly higher yields with use of very small amounts of chemical amendments (Sharma *et al.*, 2011; Singh, 2009).

Alternate Land Use Systems: A number of salt tolerant agro-forestry and fruit trees, shrubs, grasses and medicinal and aromatic plants have been identified for commercial cultivation in salt-affected soils. Some of the promising agro-forestry species are *Prosopis juliflora*, *Acacia nilotica*, *Tamarix articulata* and *Casuarina equisetifolia*. A *Prosopis juliflora*-*Leptochloa fusca* silvi-pastoral model has been found promising for sustained fuelwood and forage production in high pH soils. When followed for little more than four years, the tree and grass cover reclaims sodic soils to such an extent that normal agriculture crops such

as *Trifolium alexandrinum* and *T. resupinatum* can be grown successfully (Singh *et al.*, 1994). Appropriate planting techniques have been standardized for raising tree plantations in saline (sub-surface planting, ridge-trench method, sub-surface planting and furrow irrigation system) and sodic (ridge-trench method, auger-hole method, pit auger-hole method, pit-auger hole and furrow method) soils (Sharma *et al.*, 2014b). Different fruit-based agro-forestry systems, with bael (*Aegle marmelos*), aonla (*Emblica officinallis*) and karonda (*Carissa congesta*) as tree components and cluster bean (in *Kharif*) and barley (in *Rabi*) as subsidiary components, have been found practically feasible and remunerative with the use of moderate (EC_{IW} between 4.0 to 5.8 dS m⁻¹) to high (EC_{IW} between 8.2-10.5 dS m⁻¹) salinity waters (Dagar *et al.*, 2008). The saline and sodic lands under long-term tree cover exhibit overall improvement in soil quality which is attributed to increase in soil organic carbon and nitrogen contents, enhanced microbial biomass, microclimate modification under tree cover and nutrient uptake from deeper layers by the tree roots (Sharma *et al.*, 2014b). Different medicinal and aromatic plants such as isabgol (*Plantago ovata*), aloe (*Aloe barbadensis*) and kalmeg (*Andrographis paniculata*) produce high biomass under saline (EC_{IW} 8.5 dS m⁻¹) irrigation (Tomar and Minhas, 2004).

Bio-drainage to Combat Waterlogging and Secondary Salinity: In many canal irrigated arid and semi-arid regions of the country, waterlogging and the subsequent secondary salinization have turned vast stretches of agricultural lands unproductive. Water seepage from canals and faulty on-farm water management practices together create shallow water table conditions and significant increase in root zone salinity due to higher capillary salinization (Chhabra & Thakur, 1998). Conventionally, waterlogged saline lands are reclaimed by installation of sub-surface drainage systems which are expensive, difficult to operate and pose problems in the disposal of saline drainage effluents (Chhabra & Thakur, 1998; Ram *et al.*, 2011). These operational difficulties have generated interest in other viable alternatives such as bio-drainage for harnessing the productivity of waterlogged soils (Ram *et al.*, 2011).

Bio-drainage refers to the bio-energy driven pumping out of excess soil water and dissolved salts through rapid transpiration by the perennial trees (Heuperman *et al.*, 2002). Analogous to energy-operated water pumps, it is a proven technology to prevent salinity build-up in canal commands when suitable tree species (e.g., eucalyptus, popular, and bamboo) are raised in the beginning to prevent waterlogging and salinization (Singh, 2009). The Institute has spearheaded bio-drainage research and significant breakthroughs have been made in cheap and environment-friendly amelioration of waterlogged saline soils (Chhabra & Thakur, 1998; Ram *et al.*, 2011; Sharma *et al.*, 2011). Of late, combined applications of bio-drainage and suitable land modifications are being explored to productively utilize the waterlogged salt affected soils (Sharma *et al.*, 2011).

Saline Aquaculture: The emergence of the twin problems of waterlogging and salinity in many parts of south-western Haryana and Punjab has necessitated development of alternative approaches for productively utilizing these difficult to reclaim lands. The degraded soil and water resources in these regions can be put to profitable use by shrimp and fish farming (Purushothaman *et al.*, 2014). In fact, inland saline aquaculture (land-based aquaculture using saline groundwater) is being commercially practised in many saline tracts of Australia, Israel, and USA (Allan *et al.*, 2009). Consistent with national priorities, as outlined in the 11th 5-Year Plan of ICAR, CSSRI, Karnal has made vigorous efforts to demonstrate the practical feasibility of commercial fish culture in extreme saline environment at Nain Experimental Farm, Panipat, Haryana. In spite of constraints such as high salinity of pond water (25 dS m⁻¹), low water availability and high evaporative losses, fish growth was about 400-600 g in 6 months and 600-800 g in 1 year period (CSSRI, 2013).

Multi-enterprise Agriculture Model: Keeping in view the specific requirements of small and marginal farmers in post-reclamation phase, an integrated multi-enterprise model consisting of diverse components (field and horticultural crops, fishery, cattle, poultry and beekeeping) has been developed for 2 ha area for ensuring sustainable resource use efficiency, high and regular incomes and employment generation. This model substantially reduces the production costs by synergistic recycling of resources among different components. Similar models are also being standardized for waterlogged sodic soils in Uttar Pradesh, highly saline black soils in Gujarat and coastal saline soils of West Bengal (Sharma and Chaudhari, 2012; Singh, 2009).

Resource Conservation Technologies: In India, substantial increase in food production and a multitude of environmental problems co-evolved during Green Revolution of 1960s-1970s characterized by the heavy and indiscriminate use of agro-chemicals in rice and wheat crops. Many present and emerging challenges such as stagnating yields, decreasing factor productivity, fast receding water table, climate variability, deteriorating soil health, environmental pollution and secondary salinization have posed threats to the sustainability of rice-wheat cropping system in the Indo-Gangetic plains of India (Aggarwal *et al.*, 2004). In this backdrop, increased adoption of resource conservation technologies is imperative and ICAR-CSSRI, Karnal has made significant contributions in this direction by successfully demonstrating the efficacy of different technologies- zero tillage in wheat, direct seeded rice, residue incorporation and mulching, sprinkler irrigation- in optimizing resource use by rice and wheat crops for sustained and profitable production and improvement in physico-chemical and biological properties of the soils (Sharma and Chaudhari, 2012).

Microbial Crop Growth Enhancers: Taking a note of the fact that bio-fertilizers and microbial inoculants favourably enhance crop growth and productivity in stressful saline

environments, but their use is hampered by higher costs and lack of technical knowledge, research efforts have been made to develop low-cost microbial crop growth inoculants. A low-cost microbial bio-formulation 'CSR-BIO', based on a consortium of *Bacillus pumilus*, *Bacillus thuringiensis* and *Trichoderma harzianum* on dynamic media, has been developed and disseminated to farmers. It acts as a soil conditioner and nutrient mobilizer and increases the productivity of the high value crops like banana, vegetables and gladiolus in sodic and normal soils by 22 to 43%. It is gradually becoming popular among farmers in many states (Damodaran *et al.*, 2013)

6. EMERGING THREATS AND THE FUTURE RESEARCH AGENDA

Basic and applied salinity researches in the country in past four decades under the aegis of ICAR-CSSRI have facilitated the development of a number of cost effective technologies to augment and sustain agricultural production in salt-affected environments. These technological breakthroughs have not only been instrumental in bringing tangible improvements in the livelihoods of thousands of resource poor farmers but have also substantially improved the environmental quality in many regions having salinity and sodicity problems. Many present and emerging challenges, however, seem to be potential threats to sustainable cropping in salt-affected environments. These problems and their remedial measures are briefly discussed in the following paragraphs:

Waterlogging and Secondary Salinity in Irrigation Commands: The twin problems of excessive salt accumulation and waterlogging, often collectively referred to as secondary salinity or irrigation-induced salinity, have emerged as major obstacles in sustainable and profitable crop production in many irrigated commands of India and the problem has become particularly alarming in north-western states (Datta and De Jong, 2002; Singh *et al.*, 2010). In most of the cases, poor irrigation water management (Singh *et al.*, 2010) and clearing of perennial vegetation (Turner & Ward, 2002) induce severe salinity build-up in arable lands. The replacement of perennial trees and shrubs by annual crops results in significant increase in deep drainage and a consequent rise in water table ultimately brings dissolved salts to the upper soil layers (Turner & Ward, 2002).

The secondary salinity has caused massive land degradation in north-western India which in turn has adversely affected the agro-ecosystem sustainability rendering cultivated soils in canal commands unproductive (Singh *et al.*, 2010). In near future, if continued unabated, secondary salinity create severe environmental impacts by altering the geo-hydrological features to the extent that rapid mobilization of primary and fossil salts stored in lower soil profiles would even cause the problem of river salinization (Smedema and Shiati, 2002). According to one estimate, the potential annual monetary loss due to secondary salinity is about Rs. 1669 million in Haryana state alone where approximately half a million hectare lands are affected by this problem (Datta

and De Jong, 2002). By 2050, secondary salinity may affect 20 million ha area causing over three-fold increase in area under salt-affected soils as compared to the current estimate of 6.73 million ha (Sharma *et al.*, 2014a).

Commensurate with severity of the problem, a package of practices based on integrated water management, sub-surface drainage, cultivation of low water requiring crops, adoption of salt tolerant varieties and resource conservation practices, organic nutrient management and conjunctive use of fresh and saline waters are recommended for cost-effective and sustainable management of this problem (Singh *et al.*, 2010, Sharma *et al.*, 2014a). Emphasis should also be on precision land levelling, better design of irrigation layout and introduction of efficient irrigation technologies such as drip and sprinkler irrigation (Tyagi, 1986).

Resodification and Resalinization: Apart from the increasing menace of secondary salinity in irrigated commands (Datta and De Jong, 2002; Smedema and Shiati, 2002), the recent reports on resodification of amended alkali soils (Garg, 2002, Tripathi and Singh, 2010; Gharaibeh *et al.*, 2014) and resalinization of the reclaimed saline soils (Amin, 2004; Valipour, 2014) is a cause for concern as they could potentially ruin the prospects of sustainable cropping and could also create additional burdens on small and marginal farmers presently reeling under the adverse impacts of climate change. Resodification describes the reappearance of sodic patches in amended sodic soils through the use of gypsum or other chemicals such calcium chloride, sulfuric acid and phosphogypsum (Garg, 2002; Gharaibeh *et al.*, 2014).

The ameliorated soils support crop production for a while and gradually revert back to their original sodic state either fully or partially. The adverse conditions which favour resodification are congestion in natural drainage, shallow water tables and seasonal fluctuations in water table (Buckland *et al.*, 1986), seepage from canals and subsequent waterlogging of fields (Shakya and Singh, 2010), repeated droughts (Fekete *et al.*, 2002) and practice of crop fallow (Tripathi and Singh, 2010). The causative factors themselves point to the possible technological interventions such as efficient irrigation and drainage techniques, balanced fertilizer use with emphasis on organic inputs, cultivation of low water requiring crops and resource conservation technologies which could be adopted to ensure lasting returns from the reclaimed soils (Sharma *et al.*, 2014a).

Climate Change Induced Risks in Crop Production: Agriculture in general and smallholder agriculture in particular is extremely vulnerable to climate changes, partly because small and marginal farmers will mostly be ill-equipped to bear the high costs of climate change adaptation (Verchot *et al.*, 2007). In countries like India where majority of the small and marginal cultivators lack access to the essential crop inputs, timely agro-advisories, institutional finance and marketing facilities (Reddy & Mishra, 2009), not to talk of cutting edge crop production technologies, extreme climate events may cause widespread

distress. Abrupt climatic aberrations could prove fatal to farming in water scarce arid zones as emerging stressors (e.g., rainfall variability and repeated droughts) in addition to prevailing constraints (e.g., heavy erosion, salinity and low soil fertility) may further decrease the carrying capacity of these inherently vulnerable agro-ecosystems (Enfors and Gordon, 2007).

It is increasingly becoming evident that harmful effects of climate change- alterations in precipitation patterns, higher temperatures, repeated droughts, floods and storms, sea level rise, greenhouse gas emissions- would severely decrease agricultural productivity in arid and semi-arid climates and coastal regions. Even subtle deviations in current temperature and rainfall patterns would translate into heavy production losses in arid and semi-arid zones (Enfors and Gordon, 2007) sea level rise and the consequent increase in salt intrusion coupled with increased frequency of cyclonic storms would undermine the productivity of coastal agro-ecosystems (Yeo, 1998). As most of the arable crops are salt sensitive, even slight increase in atmospheric temperatures would cause significantly higher evapo-transpiration losses resulting in increased salt accumulation in foliage (Yeo, 1998).

Agriculture and related activities are responsible for about 10% of the global greenhouse-gas emissions which is expected to substantially increase by 2030 (Friel *et al.*, 2009). While pervasive land use changes such as deforestation result in proportionately large CO₂ emissions, agricultural activities account for about 50 and 70% emissions of methane and nitrous oxide, respectively of the total anthropogenic emissions of these gases (Cole, *et al.*, 1997). The sustainable adaptation strategies to overcome global warming are based on sustainable soil and crop management practices (resource conservation practices such as zero tillage, integrated water and nutrient management, efficient irrigation techniques and adoption of resource use efficient and stress tolerant crop varieties (Keane *et al.*, 2009) with an equal emphasis on putting the vast tracts of degraded lands (including salt-affected soils) under tree cover to for carbon sequestration and other environmental gains (Cole, *et al.*, 1997).

Multiple Stresses Adversely Impact Agricultural Productivity: In saline and sodic soils, multiple stresses such as excess toxic salts, waterlogging, anaerobic conditions, drought, heat and boron toxicity interact to adversely affect the crop growth and yield. Although simultaneous occurrence of these abiotic stresses proves lethal to plant survival, least is known about the physiological and molecular bases of plant acclimation to two or more stresses. The huge damage caused to agricultural crops by two or more different stresses highlights the need to identify and develop multiple stress tolerant genotypes (Mittler, 2006). To put this into perspective, an in-depth understanding of regulatory framework and functions of stress-induced genes are very important (Bartels, 2001). It is expected that emerging technologies such as marker-assisted selection, gene

tagging and cloning, functional genomics and proteomics could greatly expedite the conventional approaches for developing multiple stress tolerant crop cultivars.

Diminishing Supply of Chemical Amendments: There is a growing realization that traditional practice of sodic soil reclamation using amendments such as gypsum may not be feasible in longer runs. This assumption stems from the facts that amendment supplies are becoming scarce with time and that poor farmers could hardly afford the high costs involved in their use. The additional constraints in sustained use of chemical amendments include gradual reductions and/or withdrawal of government subsidies and higher market prices due to fierce competition for gypsum use between agriculture and infrastructure development projects. Restricted supply and poor quality of these amendments have also discouraged their use (Qadir and Oster, 2004). In this backdrop, prioritized research on alternative approaches such as phytoremediation using salt tolerant trees, identification of efficient microbial inoculants and organic amendments (green manures, FYM and crop residues), development of alternative amendments (pressmud, pyrite and distillery spent wash), alternate land uses and diversification through viable agro-forestry models, fruit trees and other horticultural crops and development of salt tolerant varieties has given encouraging results (Sharma *et al.*, 2011).

Water Scarcity-salinity Nexus : The importance of water as a key driver of agricultural development is reflected by the fact that only 19% of irrigated agricultural land supplies 40% of the world's food (Hanjra & Qureshi, 2010). As severe water shortages are impacting agricultural production in many parts of the world (Hanjra & Qureshi, 2010), water starved arid and semi-arid lands having a preponderance of salt-affected soils could be worst affected as salinization is increasingly seen as a major threat to sustainable crop production in these regions (Williams, 1999). If continued unabated, the nexus between water scarcity and salinity could have very serious socio-economic and environmental implications in the foreseeable future. The current global warming trends (Yeo, 1998) may also adversely impact the agro-ecosystem health and productivity in many arid climates. What is more worrisome is the fact that traditional practices of saline and sodic soil reclamation (leaching and gypsum application followed by irrigation, respectively) are water intensive and short supplies of fresh water would necessitate a paradigm shift in research and development approaches so as to use poor quality waters to reclaim and cultivate the salt-affected soils (Shrama *et al.*, 2014a).

India, which has 4.2% share of the global water resources while supports about 16.7% of the global population, agriculture accounts for lion's share (~85%) in water use. Good quality water availability in desired quantities is of utmost importance for higher agricultural productivity. Besides continuous decrease in the availability of fresh water resources, many parts in India suffering from water scarcity are also usually underlain by poor quality groundwater and

the maximum area under saline and brackish groundwaters occurs in the arid and semi-arid regions of Rajasthan, Punjab, Haryana, Delhi and Uttar Pradesh (Singh, 2009). Research priorities have been outlined to standardize the protocols for use of polluted waters in reclamation and significant achievements have been made with respect to ground water recharge, storage and subsequent use of rain water through land modification and other technological interventions such as *dorouv* technology to skim fresh water floating on the saline water (Shrama *et al.*, 2014a).

Safe Disposal and Use of Saline Drainage Effluents: The efficacy of conventional sub-surface (horizontal and vertical) drainage techniques in the reclamation of waterlogged saline lands is limited by the problems encountered in safe disposal of drainage water often containing high concentrations of salts, pollutants and toxic elements (Heuperman *et al.*, 2002). The disposal of saline drainage water into rivers, lakes and seas may be uneconomical for inland regions located far away from these water bodies. Again, localized disposal may adversely affect the soil and environmental health (Tanji & Kielen, 2002; Tripathi *et al.*, 2008). The use of evaporation ponds to dispose drainage effluents is common in countries like United States and Australia. In many cases, however, higher establishment costs and specific design requirements seem to be major impediments in the practical utility of these systems (Tripathi *et al.*, 2008). Under these circumstances, use of saline drainage water for irrigation may be an effective option for reducing the effluent volumes. The potential for irrigating with drainage water is maximized when a source of nonsaline water is also readily available. Drainage water can be applied in cyclic and/or blending modes (Shennan, *et al.*, 1995). Reuse of saline effluents could be a viable management strategy to reduce both the area affected by shallow water tables and the volume of drainage effluent requiring disposal. Salt-tolerant crops/varieties may play an important role in this strategy with the selection of crops/cultivars depending on production potential under saline-sodic conditions (Grattan *et al.*, 2004). Encouraging results have been obtained for profitable reuse of saline drainage water in wheat and other crops (pre-sowing irrigation with fresh water and subsequent use of saline and fresh water in alternate/blended modes) and further refinements are being made for enhancing the acceptability of this technology (Sharma and Rao, 1998).

7. CONCLUSION AND FUTURE THRUST

In spite of significant research breakthroughs in the management of salt-affected soils and marginal quality waters, the fast changing scenario and the emerging challenges have necessitated a paradigm shift in traditional approaches of salinity management in agriculture. In near future, the use of more robust technologies such as solute transport modelling and use of air-borne geophysical sensors should be prioritized for precise delineation of salt affected environments. Although proven and time tested, the existing technologies such as gypsum-based sodic soil reclamation and sub-surface drainage need immediate

attention for further refinements so as to make them suitable for the changing needs. Concerted efforts are also required to develop cheap and environment-friendly alternatives such as distillery spent wash- and press mud-based reclamation packages for sodic soils. The focus should now shift from breeding for salt tolerance to the development of multiple stress tolerant genotypes. The efficiency of resource conservation technologies needs to be tested at farmers' field. Research and development should go hand in hand for promoting the widespread adoption of proven salinity management technologies in an integrated mode. Sustained efforts in capacity building of the farmers so as to enable them to effectively deal with the present and future challenges will be crucial in the sustainable management of salt-affected soil and water resources.

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