Current Trends and Emerging Challenges in Sustainable Management of Salt-Affected Soils: A Critical Appraisal

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1. Introduction

Land degradation caused by the physical, chemical and biological processes severely limits the productivity of agricultural lands (Bai et al. 2008; WMO 2005). Anthropogenic activities accentuate the extent of damage caused by these natural processes and often result in severe deterioration in soil quality rendering the affected lands unsuitable for agricultural uses (Fitzpatrick 2002). Soil erosion caused by water and wind, surface crusting and soil compaction are the important physical agents causing degradation. Similarly, salinization, acidification and depletion of soil organic carbon and nutrients are the major chemical processes responsible for the decrease in soil productivity. Both physical and chemical factors coupled with intensive agricultural practices characterized by the heavy and indiscriminate use of water and fertilizers impair the soil health as evident by decreased activities of beneficial macro- and microflora and fauna in intensively cultivated and degraded soils. While currently over 2.5 billion people are directly affected by different kinds of land degradation, a large chunk of global population (~1 billion) in underdeveloped and developing countries is said to be at high risk (WMO 2005). On a geological time scale, both soil degradation and formation processes remain in steady-state equilibrium. The human quest to produce more food, for example, by land clearing and irrigation development, alters this equilibrium and shifts the balance in favour of degradation processes. Anthropogenic land degradation often occurs at a much rapid rate than the loss caused by geohydrological processes and, in extreme cases, leads to unforeseen consequences such as desertification and the consequent abandonment of agricultural lands (Fitzpatrick 2002). Besides widespread land degradation, a multitude of emerging constraints pose huge stumbling blocks to the efforts required to maintain the present and the projected food requirements. Some of these constraints include ever-shrinking availability of productive agricultural lands (Garnett et al. 2013; Lambin and Meyfroidt 2011), pervasive land use (Foley et al. 2005; Lotze- Campen et al. 2008), deforestation and biodiversity erosion (Harvey et al. 2008; Lambin and Meyfroidt 2011; Rounsevell et al. 2003), freshwater scarcity (Simonovic 2002; UN-Water 2006), climate change (Mendelsohn and Dinar 1999; Schmidhuber and Tubiello 2007) and dietary transition in many parts of the world (Kearney 2010).

In the second half of twentieth century, dramatic improvements in global food production were largely made by bringing additional lands under cultivation through the use of high-yielding varieties, chemical fertilizers and irrigation. In a rapidly changing scenario, this approach may not be viable; good quality land and freshwater resources are becoming scarce due to increased completion for other uses and massive land degradation impairing the productivity of vast tracts of agricultural lands (Garnett et al. 2013; Godfray et al. 2010). The alarming rate of natural resource degradation is evident by the fact that about 25 % of the global soil and water resources lie in a deteriorated state with adverse implications for the food security of a burgeoning world population (FAO 2011). World over, human-induced pervasive land use (e.g. shifting cultivation, deforestation, intensive cropping, infrastructure development) has proved fatal to vital ecosystem functions and services, soil health and global carbon and water budgets which are key to the sustainable human future (Foley et al. 2005; Lotze- Campen et al. 2008). The growing diversion of productive lands to raise the biofuel crops such as maize and sugarcane may further accentuate the problem of food insecurity. The USA, for example, presently accounts for over 70 % of global maize exports, and the soaring number of bioethanol 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).

The need to ensure food security while maintaining the ecological balance requires that protected territories and forests are not encroached for crop production. The contemporary trends in many developing countries, however, sharply deviate from this prerequisite as efforts to maintain sufficient food reserves have often accelerated deforestation and land conversion. It is argued that a judicious mix of innovative crop production strategies, land-use zoning, more investments in agricultural research and development and policy changes could be a strategic choice to overcome the likely trade-off between food production and land loss (Lambin and Meyfroidt 2011). The fact that agricultural intensification accentuated the problems of land degradation, deforestation and biodiversity depletion is beyond any doubt (Harvey et al. 2008; Rounsevell et al. 2003). Besides intensive land use, globalization, industrialization and sociocultural changes are also responsible for a transition from the traditional diversified farming systems to the mechanized and profit-oriented agricultural production (Harvey et al. 2008). Agricultural land use profoundly impacts the ecological balance as evident from the long-term changes in soil quality, water balance and biodiversity (Rounsevell et al. 2003). Considering the fact that intensive land management is not compatible with the environmental integrity, alternative approaches such as integrated landscape management (Harvey et al. 2008) and sustainable intensification of agriculture (Garnett et al. 2013) have been suggested to ensure a balance between agricultural production and environmental sustainability. Sustainable intensification of agriculture is essentially based on four principles of increasing food production while lessening the pressure on the existing croplands as well as arresting the harmful spillover effects of energy-intensive cropping. First, the existing loopholes in food supply systems necessitate the concerted efforts to curtailing the food wastages, developing efficient supply chains and moderating the demand for water- and energy-intensive foods such as meat and dairy products. Second, technological interventions to address the current yield gaps in major crops should duly consider the environmental sustainability concerns. Third, in some cases, even minor yield reductions or land reallocation may be desirable to ensure marginal improvements in environmental quality. Finally, the merits and demerits of each available option (i.e. conventional, high-tech, agro-ecological and organic) should be cautiously weighed so as to devise location- and context-specific strategies for sustainably harnessing the productivity of agricultural lands (Garnett et al. 2013).

The contemporary concerns for sustainable development place a critical emphasis on water which could be the most critical natural resource for sustainable human living in the twenty-first century (Lazarova et al. 2001; Islam et al. 2007). Rapid growth in world population and the global economic transformation have substantially increased the demand for fresh water (Simonovic 2002) resulting in a ‘freshwater crisis’ with 20 % of the global population lacking access to the safe drinking water (UNEP 2002). Presently, severe water stress affects large parts of China and India. As irrigated agriculture accounts for a major chunk of total water use in these countries, water shortages are decreasing their capacity to produce enough food (UN-Water 2006). Despite having about 17 % of the world’s population, India is endowed with only 0.04 % of the world's available water resources. Annual per capita water availability in India, extremely low in some regions (e.g. 300 m^3 in Sabarmati basin) but very high (e.g. 13,400 m^3 in Brahmaputra-Barak basin) in others, has decreased from 4000 m^3 to 1869 m^3 in the last two decades and is expected to decrease below 1000 m^3 by 2025 (Babel and Wahid 2008). At present, the total global water resources are calculated at 110,000 km^3 $year^{-1}$, of which green (water in the soil) and blue (water in rivers and groundwater) water pools constitute roughly 64 % and 36 %, respectively. Out of total global water availability, the total amount of water required to produce food is about 5200 km3 $year^{-1}$. Out of this amount, approximately 46 % is used to produce meat and meat products, while about 23% goes in cereal production. The huge differences in water use in production of different commodities thus necessitate careful analysis to understand the global water and energy dynamics in relation to total calorie intake, environmental footprint and national food policies of different countries (Lopez- Gunn and Ramón Llamas 2008).

The high vulnerability of agriculture to climate change, particularly in developing countries where majority of the farmers have poor adaptive capacity (Mendelsohn and Dinar 1999), is attributed to both direct and indirect impacts. Among the direct impacts, anticipated changes in rainfall pattern; elevated mean surface temperature; increased frequency of droughts, floods and storms; and sea level rise are well documented. While marked shifts in temperature and precipitation will significantly increase the cropland area in high-altitude temperate regions, low-altitude regions in developing countries will face reduced availability of prime agricultural lands. Increased frequency of extreme events such as heat waves, floods and droughts will prove more catastrophic in environmentally degraded areas. The indirect impacts of relevance to global food security will be due to reduced food supplies, higher food prices, difficulties in safe access to food and a range of food safety issues (Schmidhuber and Tubiello 2007). World over, major shifts in food consumption with a gradual transition from food grains to diversified diets are increasingly becoming noticeable. Globalization-led structural changes in agro-industrialization and food marketing coupled with a range of socio-demographic factors account for this dietary (essentially nutritional) transition (Kearney 2010). Significant increase in consumption of processed food and dairy products, meat and fish ascribed to them higher purchasing power is bound to increase the pressure to produce more nutritious food (Godfray et al. 2010) often at the cost of a high environmental footprint owing to the increased use of water and energy-intensive inputs in food production, processing and transport (Rijsberman 2006; Godfray et al. 2010).

The concerns to feed an exponentially growing world population on the one hand and arresting the shrinkage of productive land resources on the other have enhanced the scientific and political attention to tap the potential of degraded lands. This consideration stems from the fact that even marginal yield gains from such deteriorated land resources (e.g. salt-affected lands) would make a large difference to the global food output. This line of argument is even more relevant to those agricultural regions where heavy investments have been made to improve the irrigation and drainage infrastructure. While long-term strategic plans to improve the land quality will remain all important, immediate focus should be on provisional measures of salinity mitigation to harness the dividends in offing (Qadir et al. 2014). Keeping in view the fact that land is a finite resource, strategic rehabilitation plans for the degraded lands as well as the technological measures to arrest the likely deterioration inland quality in the future will be equally important. A variety of approaches-engineering, agronomic and biological- are suggested to restore the productivity of marginal and degraded lands. Depending on context-specific requirements and the likely stumbling blocks in the technology implementation, a well thought of blend of available technological interventions will give the best results. This article presents an overview of salinity research in India in the last five decades. Based on a critical review of literature, current global trends in the sustainable management of salt-affected lands are presented, and their practical utility with special reference to developing countries is discussed.

2. Salt-Affected Lands: Social and Environmental Costs

Although a bulk of salt-affected soils have originated due to natural causes, the recent salinization trends are warning signals in that human-induced salinity affects about 2 % of the global dry lands and 20% of the irrigated lands. Notwithstanding the disproportionately small share of irrigated land (~15 %) in the total cultivated land, it is worrisome that unabated salinization continues to despair their high productivity which is almost two-fold higher than the yields obtained in dry lands (Munns 2005). The annual rate of new irrigation-induced salinization is estimated at 0.25-0.5 million ha globally (Wicke et al. 2011). Massive secondary salinity in cultivated lands was partly responsible for the collapse of Mesopotamia civilization in the Euphrates and Tigris river valleys. It is believed that faulty irrigation practices caused excessive salinity build-up in cultivated lands such that wheat and even salt-tolerant barley crops failed to grow (Pitman and Läuchli 2002). Available evidences are ample to prove that some of the fertile regions of the world have been suffering from salinity threat for many decades. In many dryland (Fitzpatrick 2002; Lambers 2003; Stirzaker et al. 1999) and irrigated (Abdel- Dayem et al. 2007; Datta and DeJong 2002; Fayrap and Koc 2012; Houk et al. 2006; Qureshi et al. 2008) regions of the world, the problem of secondary salinity is becoming severe with each passing day. Consequently, some of the highly productive tracts, once the backbone of national food security in many countries, have become unproductive.

Dryland salinity is a major threat to arable cropping in Australia where it affects about 1.8 million ha agricultural lands in the wheat belt of Western parts. Given the current trends, over 8 million ha of productive soils in the region could face huge salinity risks by 2050. Land clearing for agricultural development replaces the native perennial vegetation by the annual crops and alters the water balance such that considerably high deep percolation occurs beyond the crop root zone (Lambers 2003). Owing to their shallow rooting depth and seasonal growth, the long-term average water use by annual crops and pastures is far below that of perennial trees and shrubs. The average deep drainage in drier regions has increased from <0.1 mm year−1 in the preclearing phase to >10 mm year^{-1} at present. Unrestricted water leakage beyond the root zone causes gradual rise of the water tables (~0.5 m year^{-1}) resulting in salt movement from subsurface to the surface layers (Stirzaker et al. 1999). A set of measures involving the improved agronomic practices to increase crop water use, integration of perennial pastures into crop rotations, engineering solutions to dispose the excess surface and/or groundwater and planting of trees and shrubs are suggested to tackle dryland salinity menace (Stirzaker et al. 1999). The main priority should, however, always be to raise perennial plantations to arrest the water table rise. Depending on the location-specific needs, either herbaceous (pastures or crops) or woody (trees and shrubs) species, may be grown. In areas having shallower water table, the use of salt-tolerant plants and drainage interventions (e.g. deep open drains) may be necessary (Pannell and Ewing 2004).

Sustainable productivity of rice-wheat cropping system, practiced in about 12 million ha area in South Asia, is of paramount importance to the regional food security. In recent past, however, decreasing factor productivity and yield stagnation ascribed to different biotic and abiotic constraints have markedly reduced the profits and raised concerns over the sustainability of the system (Fujisaka et al. 1994). In this context, development of the vast tracts of waterlogged saline lands due to excessive water use in many parts of Northwest India has also emerged as a formidable constraint to the viability of this system. In addition to altering the agro-ecological balance, permanent water inundation severely limits the soil productivity, curtails the farm incomes and drastically reduces the employment opportunities and thus considerably increases the rural distress. A study from the Western Yamuna and Bhakra canal commands in Haryana, India, found that irrigation-induced waterlogging and salinity drastically reduced the crop yields, leading to dismal farm incomes and decrease in farm employment (Singh and Singh 1995). In Tungabhadra irrigation project in Karnataka state, poor irrigation and drainage managements are responsible for large-scale land degradation. For the lower left bank main canal of the project alone, the economic loss due to soil degradation has been estimated to be about 14.5% of the system's productive potential (Janmaat 2004). In Haryana state of India, the potential annual loss due to secondary salinity was estimated at Rs. 1669 million at 1998-1999 constant prices (Datta and De Jong 2002). The average annual losses due to waterlogging and salinity along the Lower Arkansas River of Colorado, USA, were estimated to be approximately US$ 4.3 million (Houk et al. 2006). Based on a review of previous estimates of salt-induced monetary losses, it was concluded that in financial terms, cumulative global crop loss was over US$ 27 billion (Qadir et al. 2014). Similar findings from other salinity-affected countries such as China (Khan et al. 2009), Egypt (Abdel- Dayem et al. 2007), Pakistan (Qureshi et al. 2008) and Bangladesh (Mirza 1998) show that besides extensive economic losses, salinity also adversely impacts infrastructure, water supplies and social stability (Pitman and Läuchli 2002). These examples show the widespread and historical shortcomings in irrigation development projects in developing countries where excess water applications and poor drainage accentuate the projected rates of soil degradation. Ultimately, persistent waterlogging and salinization greatly reduce the systems' potential than expected (Janmaat 2004).

3. The State of Groundwater Resources

Any discussion on secondary salinity and the related hazards must take into account the present state of groundwater use and management. It is because salinization in both dryland and irrigated regions is inextricably linked to groundwater dynamics. Again, as the success of salinity and sodicity reclamation programmes is largely based on the ample availability of good quality water, one must look into the emerging issues in water availability and use. Groundwater is an important and dependable source of water for agricultural, domestic and industrial sectors in India. Approximately 60% of irrigated agriculture depends on groundwater wells which have been intensively exploited for maximizing the food grain production. Large-scale rural electrification, availability of electricity at cheaper rates and the schemes to expand the tube well-irrigated area have promoted unsustainable groundwater use resulting in rapid decrease in water table, waterlogging and salinization in irrigated lands. Intensive water extraction has also increased the pumping costs and has decreased the water quality as evident from high salt and pollutant loads and excess arsenic and fluoride levels in groundwater wells in different parts of the country (Singh and Singh 2002). Groundwater depletion at an alarming rate could wreck havoc to irrigated agriculture in north-western part of India in the foreseeable future.

A recent study based on satellite observations and simulated soil water variations revealed that annual groundwater loss has attained critical levels (~4 cm) in the states of Rajasthan, Punjab, Haryana and Delhi. This study suggests that effective measures such as reduction in water withdrawal are urgently required for arresting the rapid water decline to ensure stability in agricultural production and drinking water availability to the local residents (Rodell et al. 2009). The situation is particularly grim in many freshwater zones where fast receding water table (25-70 cm year^{-1}) in the last few decades has significantly increased the pumping costs and has decreased the water quality. Groundwater decline and the related problems can be overcome either by reducing the water withdrawal or by artificial groundwater recharge (Kumar et al. 2014). The importance of improved water management practices and efficient irrigation techniques in water saving has also been demonstrated (Ward and Pulido-Velazquez 2008). Given the compulsions to produce more food often with the aid of water-use inefficient irrigation practices, however, there is a limited scope for curtailing groundwater use in crop production, and the attempts to arrest the falling water tables through artificial recharge have gained currency. As a supplement to the natural recharge, simple artificial groundwater recharge techniques such as those based on recharge shaft and recharge cavity offer an attractive option to address this problem (Kumar et al. 2014).

Groundwater declines when water withdrawal exceeds the rate of natural replenishment as observed in intensively cultivated Indo-Gangetic plains of India. In Trans-Gangetic plains region comprising of Punjab and Haryana states, canal water allowance is very low, and it supplies about 150-200 mm of water to the rice-wheat cropping system (RWCS). Consequently, the farmers overly depend on saline groundwater to meet the crop water needs. The existing gap between actual water requirement (~1800 mm) and average annual rainfall (~600 mm) is responsible for the excess pumping of marginal quality groundwater and the consequent increase in soil salinity (Ambast et al. 2006). Fluoride (F^-) contamination of groundwater and the related health problems (e.g. dental and skeletal fluorosis) are gradually increasing in many parts of India (Jacks et al. 2005; Jha et al. 2013). High F^- water is not safe for human health, and about 62 million inhabitants in the states of Tamil Nadu, Andhra Pradesh, Gujarat, Madhya Pradesh, Punjab, Rajasthan, Bihar and Uttar Pradesh are at risk of F^- exposure. Although weathering of rocks is the main source of F^-, atmospheric depositions, industrial emissions and certain phosphorus fertilizers also contribute its small amounts to soil and water. Earlier considered to be a problem unique to the hard rock regions, F^- contamination is increasingly becoming an environmental issue in sodicity-affected irrigated lands (Jacks et al. 2005). Evidence is growing that areas having residual alkalinity ($Ca^{2+} < HCO_3^-$) in groundwater are particularly sensitive to F^- contamination. Evapotranspiration of groundwater having residual alkalinity lowers the Ca^{2+} level with a concurrent increase in Na/Ca ratio favourable to F^- build-up (Jacks et al. 2005; Jha et al. 2013). Keeping in mind the relation between sodic conditions and high- F^- groundwater, attempts have been made to study the effects of excess F^- in groundwater on crop growth and physiology so as to develop cost-effective solutions to mitigate this problem in the affected regions. Irrigation with F−-contaminated water increased F^- accumulation in grains of rice and wheat crops, and the concentration was found to be above safe limits for human consumption (Jha et al. 2013). The safe use of F—contaminated water in non-edible economic crops such as *Populus deltoides* has also been suggested (Singh et al. 2013). Given the dwindling gypsum supplies, a set of surveillance and monitoring programmes coupled with efforts to explore the safe use ofhigh-F− water in non-edible crops seem to be a good option to alleviate this problem in sodic lands. The problem of high arsenic (>0.05 ppm), earlier endemic to West Bengal, is gradually increasing in many regions of India. High arsenic causes darkening and pigmentation of the skin and may lead to skin carcinoma (Chowdhury et al. 1999).

4. The Problem of Poor Quality Water

While freshwater reserves are declining at an alarming rate, the problem of poor quality water has also increased with the passage of time. As agriculture accounts for a major chunk of freshwater use, it becomes imperative to explore the strategies for optimizing cost-effective, environment-friendly and sustainable use of available water resources in crop production.

Decrease in the availability of good quality irrigation water due to increasing population in urban areas and industrialization in many developing countries (Yadav et al. 2002) may aggravate in the future, and changing scenario would necessitate appropriate water management strategies, restricted irrigation and even the use of poor quality water for sustaining crop production (Oster 1994). Poor quality water (PQW), also referred to as marginal quality water, is a collective term for wastewater, saline and sodic water and agricultural drainage water. In many regions of the world, farmers irrigate their crops with untreated wastewater (domestic and industrial effluent) with potential environmental and health risks as untreated wastewater often carries injurious heavy metals, metalloids, pathogens and residual drugs. Contrary to wastewater, saline and sodic water contains toxic salts that suppress the plant growth and cause heavy reductions in crop yield. Continuous use of saline and sodic water may also cause waterlogging and secondary salinization (Qadir et al. 2007). Inadequate availability of good quality water and the lack of wastewater treatment facilities are the reasons which compel many farmers to use untreated wastewater in irrigation (Qadir et al. 2007). Similarly, two factors- predominance of saline aquifers in arid and semiarid zones and increasing competition between agriculture and other sectors for freshwater use- compel the farmers to use saline and sodic water in agricultural production (Shannon and Grieve 2000). This is the case in (semi)arid northwestern India, where in many cases saline groundwater is the only viable option available to the farmers. In such regions, saline, sodic and saline-sodic water constitute about 20, 37 and 43 %, respectively, of the total poor quality groundwater. As good quality canal water is available in limited amounts, farmers use a blend of saline water and canal water to irrigate the crops which comes with yield penalty and causes salt accumulation in soil (Kaledhonkar et al. 2012).

Precise estimates are not available regarding the extent of wastewater use in arable crops. In most of the cases, either untreated or partially treated wastewater is used in vegetables and some other horticultural crops by the small and marginal farmers in the peri-urban regions (Qadir et al. 2007). In many parts of the world, however, treated wastewater is also used (Zekri and Koo 1993). Long-term applications of treated wastewater did not cause any appreciable reduction in tree growth and fruit yield in citrus, and wastewater reuse required only minor adjustments in crop management practices (Morgan et al. 2008). Drip irrigation with treated municipal water was found safe in olive trees which produced fruits of acceptable hygiene. Soil properties in the top 10 cm soil were only seasonally affected as specific soil, and irrigation management practices excluded water percolation and avoided transport of exogenous bacteria to the deeper soil layers (Palese et al. 2009). In tomato, wastewater application did not cause any significant reduction in fruit yield and quality, and harvested fruits exhibited heavy metal concentrations below the permissible limit (Al-Lahham et al. 2007). A few reports on the use of untreated wastewater in horticultural crops are also available. Studies conducted in olive (Murillo et al. 2000) and different vegetable crops (Brar et al. 2000; Melloul et al. 2001; Kiziloglu et al. 2008) showed that untreated wastewater application would not be a safe option in longer runs. In potato, for example, irrigation with untreated sewage effluent significantly increased concentrations of Fe, Mn, Zn, Al and Ni up to 60 cm and that of Cu and Cr up to 30 cm soil depth. It also increased the concentrations of these elements in potato leaves and tubers (Brar et al. 2000). The factors instrumental in promoting wastewater use in agriculture, especially in arid and Mediterranean climates of both industrialized and developing countries, include freshwater scarcity, growing recognition of the importance of wastewater reuse, high costs of artificial fertilizers and the sociocultural acceptance of this practice (Mara and Cairncross 1989). Being a rich source of many essential crop nutrients, the effects of treated wastewater use may be similar to that of frequent fertigation with dilute nutrient concentrations (Maurer and Davies 1993). Water-stressed countries such as Israel and the USA (mainly the states of Florida, California and Arizona) are leaders in wastewater reuse practices (Angelakis et al. 1999). Treated wastewater is likely to be the major (~70 %) source of water for irrigation in Israel by 2040 (Palese et al. 2009). Still some other countries like Cyprus, Jordan and Tunisia have also made remarkable progress in treated wastewater use in irrigation. In these countries, where immense value of reclaimed wastewater use is fully recognized, elaborate regulations and safety standards have been put in place to ensure the environmentally safe reuse of wastewater (Angelakis et al. 1999).

In many irrigated regions of the world, marginal quality drainage water is regularly used in irrigation adding dissolved salts to the soils (Fayrap and Koc 2012). In surface irrigated soils, heavy irrigation even with good quality water will add substantial amounts of salt to the soil. For example, application of about 1900 mm fresh canal water (ECIW 0.3 dS m^{-1}) will add about 3.7 t ha^{-1} of salts to the soil profile (Ritzema et al. 2008). Groundwater in many parts of southwestern Punjab contains excessive amounts of dissolved salts and residual sodium carbonate (RSC). Irrigation water salinity ranges from 2 to 7 dS m^{-1}, and RSC is generally greater than 10 me l^{-1} up to 10 m depth (Shakya and Singh 2010). Although SSD has proved highly successful in ameliorating the waterlogged saline lands, it generates huge volumes of saline drainage water creating formidable problems in its safe disposal. This condition has prompted increasing interest in using the saline water, in conjunction with fresh water, in irrigation. Although potential uses of saline drainage water in crop production are well recognized, many issues need to be addressed to give it a wide acceptability (Sharma and Rao 1998). The use of sodic water having residual sodium carbonate in the range of 5–7 m mol L^{-1} has been considered safe for wheat-fallow rotation in moderately coarse soils. It is based on the premise that while irrigation in wheat crop would enhance the sodicity, rains in the ensuing monsoon months would favour the salt leaching (Kaledhonkar et al. 2012). Sustained use of saline and sodic drainage waters in irrigation requires the use of salt-tolerant crops, appropriate leaching to avoid deterioration of soil physical conditions and the use of amendments such as gypsum (Oster and Grattan 2002).

5. Plant Growth and Physiology in Salt-Affected Soils

Salt-affected soils (SAS) comprise of saline and sodic soils which differ in origin, physico-chemical properties and the constraints to plant growth. Due to presence of excess soluble salts (e.g. chlorides and sulphates of Na^{+}, Ca^{2+} and Mg^{2+}), saline soils exhibit saturation extract electrical conductivity (ECe) values ≥4 dS m^{-1}. The major limitations to plant growth in saline soils include osmotic stress (i.e. physiological drought) and specific ion toxicities. The sodic soils, on the contrary, have high exchangeable sodium percentage (ESP; >15) which adversely affects water and air flux, water-holding capacity, root penetration and seedling emergence. At high ESP, the clay particles disperse resulting in poor aggregate stability and impeded drainage (Munns 2005). The cell-specific events which affect key metabolic pathways and cause injury in salt-stressed plants include cell membrane damage due to electrolyte leakage and lipid peroxidation, oxidative stress caused by the free oxygen radicals, impaired leaf water relations, altered gas exchange characteristics and ion toxicities. Depending on factors such as salt concentration, crop species and growth stage, these impairments adversely affect cell physiology and functioning leading to the appearance of damage symptoms, stunted growth and yield reduction in salinized plants.

Electrolyte leakage (EL) and lipid peroxidation (LP) are two common indicators of cell membrane damage in plants under stress conditions. Considering the fact that adverse growing conditions damage the cell membranes leading to leakage of solutes into the apoplastic water, measurement of EL may provide a good estimate of salt-induced cell injury (Lindén et al. 2000). Malondialdehyde (MDA) level, a product of lipid peroxidation in plants exposed to adverse environmental conditions, is frequently used to assess the degree of salinity-induced free radical generation and oxidative damage to cell membranes (Najafian et al. 2008). As the extents of EL, LP and MDA production vary in salt-treated plants, these parameters have been widely studied to estimate the oxidative stress and cell membrane stability so as to differentiate the salt-tolerant lines from the salt-sensitive ones. Salt stress alters the integrity and permeability of cell membranes causing excessive electrolyte leakage from the cell. It has been shown that Na^+ and Cl^- ions coupled with oxidative stress cause lipid peroxidation and increase the permeability of plasma membranes in salinized plants (Mansour 2013). In salt-stressed plants, Na^+ displaces Ca^{2+} ions involved in pectin-associated cross-linking and plasma membrane binding leading to membrane damage (Essah et al. 2003). Specific membrane proteins and/or lipids, either constitutive or induced, as well as compounds such as glycinebetaine, proline and polyamines may contribute to cell membrane stability in salt-tolerant genotypes (Mansour 2013).

Although normally produced during plant metabolism, stress conditions induce rapid generation of harmful active oxygen species (AOS), also referred to as reactive oxygen species (ROS), such as superoxide radicals (O_2^-), singlet oxygen, hydrogen peroxide (H_2O_2) and hydroxyl radical (OH) in plant cells (Misra and Gupta 2006). Under stress conditions, the ability of plants to scavenge AOS is greatly reduced causing free radical levels to exceed the critical threshold. Accumulation of AOS and their interaction with biomolecules often impairs cell structure and functioning (Kochhar et al. 2003). Given their 'highly reactive' nature, the AOS disrupt cellular function by causing oxidative damage to cell membranes and organelles, vital enzymes, photosynthetic pigments and biomolecules such as lipids, proteins and nucleic acids. To overcome the potential damage, plants synthesize diverse antioxidant compounds for the detoxification and removal of the deleterious free radicals with the degree of protection depending on factors such as species/cultivar, growth stage and the type and duration of stress.

Most of the higher plants tend to decrease the leaf water potential (Ψ_W) and leaf osmotic potential (Ψ_S) with consequent changes in leaf turgor potential (Ψ_P) under saline conditions (Chartzoulakis 2005). Increasing salinity in root zone almost invariably decreases the leaf chlorophyll concentration with the extent of decrease depending on salt concentration, genotype and growth stage. Under certain conditions, however, salt-tolerant genotypes may exhibit marginal increase in leaf chlorophyll relative to control plants. Chlorophyll is a membrane-bound pigment, and its integrity depends on membrane stability. As cell membranes are damaged under saline conditions, chlorophyll seldom remains intact. Again, salt-induced increase in chlorophyllase activity and accumulation of Na_+ and Cl_- ions in the leaves accentuate the rate of chlorophyll degradation (Ali-Dinar et al. 1999; Singh et al. 2015). Decrease in photosynthesis under saline conditions is attributed to diverse limitations ranging from restricted CO_2 supply to chloroplast cells caused by stomatal resistance and reduced CO_2 transport in mesophyll cells caused by cell membrane leakage, leaf shrinkage-induced alterations in the structure of intercellular spaces and biochemical regulations. Impaired carbon assimilation in salt-stressed plants may also be due to excessive concentrations of Na^+ and Cl^- in the leaf tissue (in general above 250 mM) (Munns et al. 2006). The degree of photosynthetic recovery in salt-stressed plants depends on the magnitude and duration of salt treatment. In general, plants subjected to mild stress show fast recovery (within 1 or 2 d) after stress is relieved, but plants subjected to severe stress recover only 40–60 % of the maximum photosynthetic rate after stress is alleviated (Chaves et al. 2009).

The two-phase inhibition of plant growth in saline soils, which involves an initial osmotic shock followed by ion injuries, differs with the crop. In annual plants, salt-induced toxicity symptoms generally develop within few days, while in perennial crops salt injury may become noticeable after months or even years. It has been shown that while osmotic stress equally affects both tolerant and sensitive genotypes, specific salt effects mainly hamper the growth in sensitive lines (Munns 2005). The perennial fruit trees differ from the annual field crops in many respects when grown in saline soils. Contrary to the annuals which generally exhibit higher salt tolerance with age, most of the fruit crops tend to become salt sensitive as they grow older. It is attributed to carry over of salts stored in roots to leaves as well as slower growth rates in older plants. Again, highly salt-sensitive species such as citrus and stone fruits tend to accumulate Na^+ to toxic levels in soils which are essentially normal. Under certain conditions, Na^+ and Cl^- may not be the predominant ions in saline soils, and the use of rootstocks that restrict the uptake of these toxic ions may render specific salt effects relatively unimportant, and osmotic inhibition will thus virtually cause most of the deleterious effects in salinized fruit plants (Bernstein 1980).

6. Mechanisms of Salt Stress Alleviation

Unlike the animals, Na^+ is not essential for plants except in halophytes where Na^+ accumulation in cell vacuoles is implicated in osmotic adjustment. Animal cells respond to high extracellular salt concentrations through plasma membrane Na^+/K^+-ATPase channel-mediated Na^+ efflux and K^+ influx to establish a K^+/Na^+ ratio favourable to cell functioning. Plant cell membranes, in contrast, possess H^+-ATPase which creates H^+ electrochemical gradient for regulating the ion transport and uptake. As hydrated Na^+ and K^+ ions have a similar radius, K^+ transport channels in plants fail to distinguish between the two, and the resultant higher Na^+ influx alters the ionic balance and adversely affects a myriad of cellular processes. It has been shown that Na^+ concentrations above 100 mM induce a sharp reduction in cell K^+ levels which in turn affects the protein synthesis. It is interesting to note that many important cytosolic enzymes in both salt-tolerant halophytes and salt-sensitive glycophytes are equally sensitive to high salt concentrations (Blumwald 2000). Salt-stressed plants alleviate Na^+ toxicity either by excluding the excess Na^+ or by sequestering it in the vacuoles. After vacuoles become saturated, Na^+ ions flow to the cytosol and apoplast and affect the enzyme activities and cell turgor, respectively. Thus, both salt exclusion by the roots and Na^+ accumulation in vacuoles are the traits that confer salt tolerance to the plants (Rausch et al. 1996). Accumulation of free radicals in salinized plants enhances the activity of antioxidant molecules. The main antioxidant enzyme is superoxide dismutase (SOD). It is a metalloprotein that catalyzes the conversion of superoxide radical into hydrogen peroxide. There are several SOD isozymes: Mn-SOD, Cu/Zn-SOD and Fe-SOD. To avoid hydrogen peroxide accumulation, a compound even more damaging than superoxide radical, enzymes catalase (CAT) and ascorbate peroxidase (APX) are activated (Arbona et al. 2003). Salt-stressed plants tend to accumulate proline for overcoming the osmotic stress and cellular dehydration. The stress protection activities of proline are attributed to its involvement in osmotic adjustment, stabilization of subcellular structures and the elimination of free radicals (Hare and Cress 1997). In halophytes, proline is the major component of amino acid pool under salt stress. While proline levels remain low under nonsaline conditions, salinized plants show manifold increase in proline concentration (Stewart and Lee 1974). The increase in proline content is mostly positively correlated with the level of salt tolerance, and salt-tolerant genotypes generally show elevated proline concentrations as compared to salt-sensitive ones (Ghoulam et al. 2002). Plants facing Na^+-induced cellular toxicity tend to maintain the osmotic water balance by lowering the leaf water potential below that of soil water so as to ensure smooth water uptake for the turgor maintenance. Osmotic balance can be achieved either by solute uptake from the soil or alternatively by synthesizing compatible solutes such as proline and sugars. From an energy-use point of view, uptake and accumulation of inorganic ions such as Na^+ and Cl^- is a cheap option but with inherent danger of cellular toxicity. In contrast, osmotic adjustment though compatible organic compounds is a safe but energy-intensive strategy (Tester and Davenport 2003).

7. Salinity-Environment Interaction

Different environmental factors including temperature, humidity, light intensity and CO_2 concentration influence the crop response under saline conditions. In majority of the cases, crops exhibit greater salt tolerance when grown in cool and humid locations. The hot and dry conditions, in contrast, increase the salt stress (Francois and Maas 1994). Even subtle changes in atmospheric temperature and humidity, due to anticipated climate change, may adversely affect growth and development in crop grown in saline soils (Yeo 1998). Although it is generally agreed that prevailing weather conditions determine plant response to salinity, the non-specific nature of most of the environmental variables makes it difficult to quantify their effects on plants growing in saline media. Atmospheric temperature, however, is perhaps the least specific of all the environmental factors as it affects a range of soil and plant processes including salt dynamics in the soil and transpiration and mineral nutrition in plants that are important in relation to salinity (Gale 1975). Seed germination in *Crambe* (*Crambe abyssinica* Hochst. ex R.E. Fries), a potential oilseed crop for saline soils, was severely affected at 5 °C even in control treatments. Better germination in salt-treated plants (6.3–36.3 $dS\ m^{-1}$) was recorded at temperature range of 15–25 °C, germination peaked at 20 °C and decreased at both low (10 °C) and high (30 °C) temperature regimes (Fowler 1991). The highest seed germination and better seedling growth in salinized (516 mM NaCl) *Atriplex griffithii* var. *stocksii* plants were observed at cooler alternating temperature (25:10 °C) and inhibited at warmer (30:15, 30:20 and 35:25 °C) regimes (Khan and Rizvi 1994). In sorghum (*Sorghum bicolor* L.), salinity (6.4–37.2 $dS\ m^{-1}$) decreased the germination percentage, but effects were less severe at higher (30–40 °C) than lower (15–25 °C) temperatures (Esechie 1994). Safflower (*Carthamus tinctorius*) plants grown under different osmotic potentials (−0.3 to −0.9 MPa) and three constant temperatures (15, 25 and 35 °C) showed higher growth at 25 °C as compared to other (15 and 35 °C) temperature levels (Gadallah 1996).

Barley, wheat and sweet corn grown under nonsaline and saline media showed differential response to the low (45 %) and high (90%) relative humidity (RH) treatments. High RH enhanced the salt tolerance of barley and corn but had no effect on wheat. For all the three crops, water-use efficiency was higher at 90% than at 45 % RH at different osmotic potentials (Hoffman and Jobes 1978). High RH (90%) alleviated salt stress in onion and radish but not in beet (Hoffman and Rawlins 1971). Salt-induced growth reduction in bean plants occurred at both low and high RH levels. However, high RH conditions favoured better growth in salinized plants as compared to salt-treated plants grown under low humidity (Prisco and O'Leary 1973). It was found that high humidity conditions markedly alleviated salt stress in both cotton and bean but the effects were more pronounced in cotton as compared to bean (Nieman and Poulson 1967). These observations indicate that high humidity enables better growth in salt-stressed plants by improving the transpiration rate for sustained water and nutrient uptake (Nieman and Poulson 1967). Light irradiance also affects the growth in salinized plants. Higher reduction in growth is likely at high than low light conditions for equivalent salinities (Francois and Maas 1994). Salinized plants of strawberry cultivar

‘Rapella’ produced fruits with lower dry matter concentration when grown at low irradiance (2.1 MJ m^{-2} day^{-1}) in comparison to those grown under unshaded condition (4.9 MJ m^{-2} day^{-1}). Lower concentrations of reducing sugars in the shaded and salinized plants was attributed to salinity-induced reduction in carbon partitioning into sucrose and its restricted translocation from leaves to the fruits (Awang and Atherton 1995). The use of shade screens increased water- and radiation-use efficiencies as well as the quality of tomato fruits irrigated with saline solutions (EC_{IW} 3.1 and 5.1 dS m^{-1}). Marketable fruit yield (12.1 kg m^{-2}) under shaded 3.1 dS m^{-1} treatment was significantly higher than control plots (11.1 kg m^{-2}) greenhouse. The incidence of blossom-end rot was also remarkably lower in the shaded treatments under both salinity levels (Lorenzo et al. 2003). Spring tomato crop was grown under different climatic conditions and salinity (1.7–6.4 dS m^{-1}) levels. Under poor light conditions, high salinity usually did not adversely affect long-term production (Sonneveld and Welles 1988).

Atmospheric CO_2 concentration has increased from 270 μmol mol^{-1} in the pre-industrial era to 389 μmol mol^{-1} in 2010, and further increase is imminent due to rising use of fossil fuels. The net carbon assimilation in plants increases with increase in atmospheric CO_2 concentration resulting in an enhanced net primary production. This CO_2-fertilization effect is more pronounced in C_3 plants where photosynthesis is CO_2 limited (Lenka and Lal 2012). Most of the halophytes exhibit high water-use efficiencies under salt stress. Increase in CO_2 concentration further reduces the water loss and increases the growth resulting in even higher water-use efficiency. In spite of substantial differences in WUE, plants grown at equivalent salinities and different (normal and elevated) CO_2 levels do not exhibit differences in leaf salt concentration, indicating that salt uptake is not linked to water use (Ball and Munns 1992). Salt-stressed plants of *Phaseolus vulgaris* and *Xanthium strumarium* (both C_3 species), *Zea mays* (salt-sensitive C_4 plant) and *Atriplex halimus* (C_4 halophyte) exhibited significant increase in plant dry weight under high (~2500 μl l^{-1}) CO_2 conditions (Schwarz and Gale 1984). The interactive effect of CO_2 and NaCl on the second trifoliate leaf of *Phaseolus vulgaris* L. showed that elevated CO_2 partially overcame some salinity effects such as leaf area, volume, specific leaf area and relative leaf expansion rate (Bray and Reid 2002). Saline irrigation (150 mol m^{-3} NaCl) greatly reduced tillering in both *aestivum* and *durum* wheat cultivars. High CO_2 partly reversed the effects of salinity as evident from significantly high dry matter accumulation under salt treatment (Nicolas et al. 1993). Saline irrigation (0, 25, 50, 75, 100 % seawater salinity) in halophyte *Aster tripolium* increased the stomatal and mesophyll resistance causing a significant decrease in photosynthesis and water-use efficiency and higher oxidative stress as indicated by dilations of the thylakoid membranes and an increase in superoxide dismutase (SOD) activity. Under these conditions, elevated CO2 (520 ppm) mitigated salt stress and significantly improved photosynthesis and water-use efficiency (Geissler et al. 2009). Higher growth due to improved water-use efficiency, however, may alter the soil-plant-water balance and could cause a rise in water table bringing the dissolved salts to the surface (Munns et al. 1999). Salinity-ozone interaction studies have revealed that higher ozone concentration may either have no effect or may accentuate the effects of salinity. Garden beets (*Beta vulgaris* L.) grown in saline nutrient solution cultures having osmotic potentials of −0.4, −4.4 and −8.4 bars, respectively, were exposed for 5 weeks to 0.20 ppm ozone for 0–3 h/day. Development of foliar ozone injury symptoms in salt-treated plants was rather slow, and both shoot and root growth were relatively unaffected by ozone exposures of up to 3 h/day (Ogata and Maas 1973). Bean (*Phaseolus vulgaris* L.) plants were grown under osmotic potentials of −0.4, −2.0 and −4.0 bars and were exposed to 0, 0.15, 0.25 and 0.35 ppm of ozone. The results indicated no interaction between salinity and ozone below 0.15 ppm (Hoffman et al. 1973). In nonsalinized alfalfa (*Medicago sativa* L. cv.

Moapa) plants, ozone at 10, 15 and 20 parts per hundred million (pphm) reduced the forage yield by 16, 26 and 39%, respectively. As salinity increased, ozone had less effect on yield. Alfalfa exposed to 20 pphm of ozone for 2 h daily yielded 25% more at −200 kPa osmotic potential than control (−40 kPa) plants (Hoffman et al. 1975). Rice (*Oryza sativa* L.) varieties differing in salt tolerance were grown under saline conditions with or without a repeated exposure to ozone at a concentration of 83 nmol mol^{-1}. Both salinity and ozone reduced the plant height, leaf K^+ concentration, gas exchange and CO_2 assimilation. Ozone reduced the leaf Na+ concentration at 50 mm NaCl but had no effect upon Cl^- concentration (Welfare et al. 1996). Salinity (30 mM NaCl) considerably reduced the plant height, number of leaves and dry weights of the leaves, stems and roots. Exposure to 85 nmol mol^{-1} ozone for 6 h per day caused further growth reduction in salt-stressed plants (Welfare et al. 2002).

8. Mapping and Characterization of Salt-Affected Soils

Considering the fact that accurate delineation of salt-affected lands is one of the prerequisites for their productive utilization, concerted efforts have been made to develop updated salinity maps for different states of India. The availability of many cost-effective and robust techniques such as geographic information system and remote sensing has considerably expedited the progress in characterization of saline and sodic 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). Using appropriate models, multispectral high-resolution satellite imageries are processed into thematic maps to assess the spatial and temporal variability in salinity and alkalinity (Farifteh et al. 2006). Till date, mapping on 1:250,000 scale has been done in 15 salt-affected states, and the efforts are in progress to digitize the maps on 1:50,000 scale. By reconciling different estimates, the total salt-affected area in the 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. Availability of information regarding state-wise distribution of saline and sodic soils has proved helpful 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 and Singh 2015). The traditional approach of salinity mapping is based on intensive soil sampling and the subsequent laboratory analyses to determine soil pH, electrical conductivity and other chemical properties. However, as these methods are costly and time-consuming (Allbed and Kumar 2013; McNeill 1992), rapid, efficient and practically feasible tools are required to assess the spatial-temporal variations in salinity in crop fields (Wiegand et al. 1994). To overcome the limitations associated with conventional methods, initially in situ direct current resistivity technique was tried with limited success due to slow speed of the resistivity measurements (McNeill 1992). Over the years, the idea that apparent soil electrical conductivity (EC_a) measurements could provide a reasonable estimate of EC_e-gained currency and EC_a measurements increasingly came into use. Electromagnetic (EM) induction, electrical resistivity and time-domain reflectometry (TDR) techniques are used to measure EC_a which is influenced by different soil properties including the soluble salt, clay and water contents, soil bulk density, organic matter and soil temperature. Given that EC_e is the standard measure of salinity, the ECa values are converted into EC_e by non-linear and linear transformations (Corwin and Lesch 2005). The commonly available EM probes such as EM-31 and EM-38 (Corwin and Lesch 2005) send electromagnetic currents in the ground to measure the magnetic field strength to determine the soil conductivity. EM techniques are better suited to ‘conductive’ soils having high salt concentrations. The spacing between the transmitter and receiver coils determines the effective depth up to which EM devices can predict the salinity (McNeill 1992). In some cases, EC_e may show low correlation with EC_a due to sample-size differences, but the calculated EC_a values often accurately predict whether the measured EC_e would lie above or below some threshold value (Sheets et al. 1994). TDR technique is also employed for the simultaneous determination of soil water content and salinity (Dalton 1992) particularly in light soils with low conductivity as in heavy-textured (e.g. clay) soils surface conduction weakens the force of TDR signal (Zegelin et al. 1992). In situ TDR measurements give results comparable with those obtained by conventional non-destructive techniques (Dalton and Van Genuchten 1986). Advent of different sensor-based techniques such as aerial photography and videography, satellite- and airborne-multispectral sensing, hyper-spectral imaging and remote sensing have considerably enhanced the speed and accuracy of salinity mapping (Metternicht and Zinck 2003). Remotely sensed multispectral satellite data on salt reflectance at the soil surface are processed using techniques such as spectral unmixing, maximum likelihood classification, fuzzy classification, principal components analysis and correlation equations to yield the valid inferences. The main limitations to the use of remote sensing in the characterization of salt-affected soils include the changes in spectral reflectance characteristics of salts, spatial-temporal variations in salt concentration, interference of vegetation and the spectral confusions with other terrain surfaces (Metternicht and Zinck 2003). Of late, frontier technology-driven tools are increasingly being applied for salinity mapping and generating informative resource inventories in a short span of time. Besides broadening the existing understanding of major limitations to plant growth, these techniques have opened new avenues for the precision farming and site-specific management in salt-affected lands. Advances in computer modelling and geostatistical techniques have made it possible to characterize the spatial variability of soil chemical properties so as to identify productive crop management zones in a given saline tract (Li et al. 2007). Integrated hydro-geochemical and geophysical methods are also increasingly proving useful in assessing the extent groundwater salinity.

Different hydro-geochemical parameters (e.g. ion content, pH and total dissolved salts) of the groundwater along with geophysical tools (geoelectrical resistivity soundings and reflection seismic surveys) are used to estimate the water quality in saline aquifers. These techniques not only provide the precise estimates of salinity and ionic composition in groundwater, but they also reveal potential zones of fresh and saltwater interface for the future water management plans (Samsudin et al. 2008). A combination of aircraft surveys and in situ measurements was employed to map the surface and subsurface salinity distributions, respectively, in the Great Barrier Reef Lagoon. While airborne sensors provided rapid assessments of the spatial extent of the surface salinity, in situ measurements revealed the subsurface salinity status in detail (Burrage et al. 2003).

9. Technologies for Harnessing the Productivity of Saline Lands

Globally, about 25% (~3.2 billion hectares) of the total land area is used as arable land, i.e. land under temporary crops and pastures, market or kitchen gardens and the fallow land. The agricultural land (arable land area under permanent crops and pastures) constitutes about 40-50 % of the total global land. Sustainable soil health is of paramount importance to the survival and development of human society. These soil functions and services have become more important than ever in face of challenges such as climate change, water and energy scarcity and biodiversity loss. A precise estimate of crop and monetary losses due to salinity is very difficult. Nonetheless, it is important to note that current losses attributed to salinization are huge with at least 20% of the global irrigated lands suffering from production losses to varying degrees (Pitman and Läuchli 2002). It is increasingly being realized that technology-led productivity enhancements in salinity-affected regions would greatly relieve the pressure on prime agricultural lands. Even modest productivity gains will significantly improve the rural livelihoods in most of the resource poor and harsh arid environments suffering from the problems of soil and water salinity. A brief account of salinity management technologies and the constraints in their use are discussed under the following heads:

9.1 *Improving the Land Drainage*

Although reliable estimates are not available, twin problems of waterlogging and salinity are responsible for the massive reduction in food grain production in many parts of the world. In northwestern India, especially in parts of Haryana and Punjab states, over 1 M ha agricultural lands are affected by these problems. Beginning with some pilot drainage projects in Haryana in the 1980s, the ICAR-Central Soil Salinity Research Institute, Karnal, spearheaded the efforts in this direction, and it soon became evident that subsurface drainage (SSD) is a viable technology for restoring the productivity of such lands (Datta et al. 2004). Over the years, significant improvements in the design and drain spacing have considerably enhanced the adoption of SSD. The SSD network consists of a network of concrete or polyvinyl chloride (PVC) pipes along with filters installed manually or mechanically at a specified spacing and depth below the soil surface. Initially developed for Haryana, SSD projects have been successfully implemented in Rajasthan, Gujarat, Punjab, Andhra Pradesh, Maharashtra, Madhya Pradesh and Karnataka states (Gupta 2002, 2015). The reclaimed soils show significant improvements in soil properties and give considerably higher crop yields. In spite of tangible gains such as higher incomes to the land owners, generation of farm employment and improvements in environmental quality, both implementation and the maintenance of SSD projects face many socio-economic constraints. While higher initial costs restrict the implementation in many cases, prohibitive maintenance costs and the lack of community participation are responsible for project failures at majority of the sites. This state of affairs underscores the importance of active community involvement as a key to the success of SSD projects (Ritzema et al. 2008). In light of defunct or weak community management due to disparity in benefits from drainage, differences in the socio-economic backgrounds of the members and conflict of interest between head and tailenders, a co-operative institutional set-up has also been suggested (Datta and Joshi 1993). Besides these socio-economic constraints, disposal of saline drainage effluents is another limiting factor especially in the landlocked locations. A number of strategies such as the use of evaporation ponds (Tripathi et al. 2008), blended or cyclic use of saline and fresh (Datta et al. 1998) and the use of salt-tolerant cultivars (Sharma and Rao 1998) are suggested for enhancing the acceptability of this technology at farmers' fields. Impeded drainage in coastal lands is due to heavy and concentrated downpour, flat land topography, poor water infiltration and the lack of well-defined drainage systems. In poorly drained lands, continuous use of even marginally saline water (2 dS m^{-1}) causes salt accumulation (Yadav et al. 1979). Heavy-textured soils in low-lying zones are particularly sensitive to waterlogging. The presence of excess amounts of insoluble humic acid in coastal soils of West Bengal adversely affects their water permeability. These soils also exhibit poor sorptivity characteristics which significantly reduced their ability to absorb the water during infiltration. Deep tillage, addition of sand and vertical drainage may enhance hydraulic conductivity in these soils (Raut et al. 2014). In low-lying heavy soils having poor hydraulic conductivity, surface drainage to remove the excess water suffers from the lack of natural outlets and backwater flow (Ambast et al. 2007). A few preliminary studies conducted in the decades of the 1960s and 1970s provided useful insights for the reclamation of coastal saline soils by subsurface drainage. The results obtained with respect to the method, depth and duration of ponding and the type of drains to be used encouraged further attempts in this direction. In soils having very poor hydraulic conductance (2–10 cm day^{-1}) in the upper 1.5 m profile, drain spacing of 15 m with a depth of 1.75 m and a length of 35 m gave the best results in combination with water ponding (Yadav et al. 1979). In heavy-textured coastal saline-sodic soils, closer drain spacing (15 m) proved more effective as compared to wider spacings in terms of rice grain yield. Considerably lower rice yields obtained with wide drain spacings (35 and 55 m) were attributed to the heavy loss of ammonium form of nitrogen through the drainage effluent resulting in limited availability of total nitrogen to the plants (Singh et al. 2001). Limited practical utility of surface and subsurface drainage interventions in coastal soils, however, has generated interest in other techniques for salt leaching by improving the physical properties and hydraulic conductivity. For example, sand application at the rate of 30 % by volume and soil mulching with rice husk (10 t ha^{-1}) significantly improved the water flux leading to salt displacement to the lower profiles. Round-the-year rice cultivation with good quality water (ECiw ~1.5 dS m^{-1}) has also been found effective in reducing the salt content in the soil apparently due to salt leaching due to continuous ponding of water (ICAR-CSSRI 2015).

9.2 *Land Shaping Models*

It has been shown that landscape characteristics affect the soil water flow, soil development and soil change and are linked to land degradation. An understanding of the interplay between these processes may be of great help in developing appropriate and efficient management strategies to arrest the land degradation (Fritsch and Fitzpatrick 1994). Soils having better water permeability are amenable to land-use intensification through simple agronomic practices such as early crop sowing, replacement of less productive land races with high-yielding cultivars and integration of crop and high value components. Multiple cropping and increase in crop yields literally translate into enhanced availability of food, feed and energy from the same land unit. A combination of crops and other components increases the availability of diverse food resources to the farm families (Saleem and Astatke 1996). The usefulness of a few simple and economically viable land shaping techniques including farm ponds and paddy-cum-fish model for enhancing the productivity of degraded waterlogged saline lands has been demonstrated (Ambast et al. 1998). Soils having poor water permeability often suffer from the problems of water inundation and salinity. Rainwater harvesting in such man-made structures serves twin purposes of salinity mitigation and enhanced availability of irrigation water during the dry season. Establishment of the farm ponds involves the excavation of about 20% of the farm soil from a depth of about 3 m. The excess rainwater is harvested in these ponds for irrigating the crops grown on embankments round the year. In addition to fish rearing in the pond and crop production on dykes, there are ample prospects for integrating other components such as poultry and duckery to further enhance the land value while promoting the resource conservation and recycling among the different components. In paddy-cum-fish model, trenches (3 m top width × 1.5 m bottom width × 1.5 m depth) are dug around the periphery of the farmland leaving about 3.5 m wide outer from boundary, and the dugout soil is used for making dikes (about 1.5 m top width × 1.5 m height × 3 m bottom width) to protect 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, the remainder of the farmland including the trenches is used for integrated rice-fish culture (Mandal et al. 2013). Severe waterlogging is one of the major constraints in productive utilization of vertisols in Ethiopian highlands. The conventional surface drainage approach to overcome this problem has not given desirable results, and accordingly focus has shifted to alternative technologies for improving the crop yields. These approaches including broad bed and furrows (BBF) and ridge and furrows (RF), often in combination with green manuring and reduced tillage, have improved land quality and crop yields at many locations (Abebe et al. 1994; Erkossa et al. 2004; Erkossa et al. 2006) mainly by enhancing the drainage. The extent of drainage effect on crop yields was dependent on rainfall quantity, clay content and crop species (Abebe et al. 1994). Many economically viable land shaping technologies have become successful in coastal saline tracts of the country, and efforts are in progress to demonstrate their utility under waterlogged saline and sodic conditions in inland regions of the country (Sharma and Chaudhari 2012).

9.3 *Techniques for Groundwater Recharge*

Different simple practices of groundwater recharge in water-stressed north-western parts of India have been discussed by Kaushal (2009). These include rooftop rainwater harvesting, recharge through recharge wells, village ponds and surface drainage network and water conservation in rice fields. Rooftop rainwater harvesting arrests the soil erosion, reduces the flood hazard and improves the groundwater quality. The use of recharge wells to capture the surface runoff, rehabilitation of village ponds to provide irrigation and recharge underground aquifers and utilizing the vast drainage network constructed for flood control also significantly improve the groundwater resources. Rainwater conservation in paddy fields to control the declining water table by reducing the groundwater draft and enhancing the groundwater recharge should also be given focus. Again, enactment of appropriate legislations at national and state levels to prevent indiscriminate exploitation of the water resources is urgently required. Groundwater in the rice-wheat sequence in the Trans-Gangetic plains of India is either fresh or marginally saline. While tube well density is high (15 km^{-2}) in most of the freshwater zones, it is considerably low in the poor quality groundwater areas, where annual rainfall is less than 400 mm and cotton-wheat, pearl millet-wheat and pearl millet-mustard are the main cropping sequences. Under rice-wheat cropping sequence, groundwater is declining in both fresh and marginal quality groundwater zones. In contrast, water tables are rising in dry zones having poor quality water. In parts of Punjab (Jalandhar, Ludhiana, Moga, Bathinda, Sangrur and Patiala districts) and Haryana (Kurukshetra, Karnal, Kaithal, Jind and Panipat districts), water table has receded by 5-15 m in the last three decades requiring the replacement of centrifugal pumps with submersible pumps leading to more use of energy and higher pumping costs. As any significant decrease in groundwater withdrawal does not seem feasible in the foreseeable future, increase in groundwater recharge through man-made structures including percolation tanks, check dams, recharge tube wells and rainwater harvesting should be given emphasis (Ambast et al. 2006).

9.4 *Irrigation Management*

Given that decreased freshwater supplies are imminent in the future due to increased municipal-industrial-agricultural competition, available water must be used efficiently (Qadir and Oster 2004). Water use in agriculture, industrial and domestic sectors is 75%, 20% and 5 % of the total global consumption (UNEP 2002). The use and reuse of enormous amounts of saline and/or sodic drainage effluents in irrigation will increasingly become necessary (Qadir and Oster 2004). Predominance of saline groundwater aquifers poses a serious limitation to the sustainability of rice-wheat cropping system in India. A set of measures including reduced frequency of irrigation and enhanced irrigation water volumes, replacement of surface irrigation methods with efficient techniques such as sprinkler and drip irrigation, the use of salt-tolerant crops and cultivars, conjunctive use of fresh and saline water, improved fertilizer management and the use of amendments is suggested to overcome many of the problems related to saline irrigation. Either blended or cyclic use of canal water and saline water is desirable in most of the crops. Additional doses of phosphorous and organic manures may be required to alleviate Cl^{-} toxicity and improved nitrogen use efficiency, respectively (Minhas 1996). Site-specific management practices may enable long-term sustainable use of saline drainage water which is influenced by different factors including the extent of salt leaching, crop establishment method, total rainfall and subsurface drainage. The use of saline drainage water in reclaimed soils will lessen the pressure on freshwater reserves and will also partly reduce the environmental impacts of effluent disposal (Sharma and Tyagi 2004). Due to significant reduction in water consumption, application of nutrients with water (fertigation) and ease in the use of marginal quality water, drip irrigation is increasingly becoming popular in perennial row crops and fruit trees. The use of poor quality water through drip, however, requires some changes from standard irrigation practices such as selection of appropriately salt-tolerant crops. When using low quality water, drip irrigation has several advantages over other irrigation methods because it does not wet the foliage, and because of its high application frequency, concentrations of salts in the rooting zone remain manageable (Mmolawa and Or 2000). Besides considerable reduction in water-use and energy-use costs coupled with the significant increase in yield, direct water application into root zone means virtually no surface runoff considerably arresting the rate of soil displacement.

As irrigation channels and bunds are not required, additional lands can be put under crops. Addition of soluble nutrients and pesticides in irrigation water means efficient use of these resources resulting in reduced cost of cultivation and control of environmental pollution as agrochemical loads into soil and groundwater are minimized (Singh et al. 2007). Long-term use of saline water through surface drip may result in gradual downward movement of salts to the root zone increasing osmotic stress and salt toxicity to the crops. The assumption that such salt accumulation can be overcome by adopting the subsurface drip irrigation (SDI) is based on the premise that salt front is partially driven down into the deeper soil bulk and to the periphery of the root zone under SDI and thus minimizing the risk of damaging the main roots of the plants. Moreover, the improved moisture conditions in the vicinity of the emitter offset the inhibiting effects of the presence of the salts in the saline water (Oron et al. 1999). Subsurface drip irrigation (SDI) refers to the application of water below the soil surface through emitters with discharge rates mostly equal to the surface drip. In general, drip tubes placed 2 cm below the soil surface are considered under SDI (Camp 1998). Subsurface drip systems have been specifically designed for row-planted field and vegetable crops to ensure that surface pipes do not hinder the intercultural operations. They are similar in design but vary with the surface drip in that tubings are buried. In addition to the advantages of surface systems, SDI curtails the water loss due to evaporation and deep percolation and virtually eliminates the surface runoff. It also permits precise application of water and nutrients in the root zone (Roberts et al. 2009).

9.5 *Use of Chemicals and Amendments*

Excess exchangeable Na^+ in sodic soils is replaced by the application of chemicals and amendments rich in Ca^{2+} followed by leaching with good quality water. A range of factors including the degree of sodicity, depth of reclamation, amendment to be used and crops to be grown determine the extent of reclamation. The efficiency of an amendment vis-à-vis other available options, effects on soil properties and crop growth and the likely expenditure are the major guiding principles in sodic soil reclamation programmes (Abrol et al. 1988). Depending on soil chemical properties, either direct (e.g. gypsum) or indirect (sulphuric acid, elemental sulphur, etc.; Horney et al. 2005) forms of calcium may be applied. In soils low in carbonate, application of gypsum is recommended. Similarly, high carbonate soils may be reclaimed using sulphuric acid and other indirect sources of calcium (Horney et al. 2005). Gypsum is the most widely used amendment in sodic soils. It is, however, becoming evident that gypsum may not be available in desired quantity and quality in the future. While gypsum supplies are becoming scarce with time, both higher costs and poor quality prohibit its use by the farmers. It is likely that gradual reductions in government subsidies and higher market prices will further decrease gypsum availability and use (Qadir and Oster 2004). This state of affairs has enhanced the interest in organic inputs, alternative amendments and nanoscale materials in sodic soil reclamation. It has been shown that the use of easily available and cheap organic amendments increases the productivity of salt-affected lands as organic matter input often accelerates salt leaching and improves aggregate stability, water flux and water-holding capacity (Walker and Bernal 2008). Application of organic inputs such as green manure (Rao and Pathak 1996), farmyard manure (FYM; Ahmed et al. 2010), poultry manure (PM; Tejada et al. 2006), municipal solid waste compost (MSWC; Lakhdar et al. 2009), rice straw (Liang et al. 2005) and olive mill waste compost (OMWC; Walker and Bernal 2008) improves the soil environment and enables better plant growth in salt-affected soils. Incorporation of *Sesbania cannabina* green manure in highly saline and alkali soils improved the physico-chemical and biological properties as evident from significant reductions in soil pH and exchangeable sodium, increase in soil carbon and nitrogen and enhanced activity of urease enzyme (Rao and Pathak 1996). Saline soils (ECe ~9 dS m^{-1}) treated with PM at 10 t ha^{-1} exhibited almost tenfold increase in plant stand (~80 %) as compared with sparse vegetation (~8 %) in control soil. Organic matter addition increased the soil structural stability, improved the soil aeration and enhanced the microbial biomass. Amended soils showed high water soluble carbohydrates and better biochemical properties as compared to control plots (Tejada et al. 2006). Application of MSWC enhanced salt tolerance of salinized (4 g l^{-1} NaCl) *Hordeum maritimum* L. plants presumably due to improved chlorophyll and protein stability and higher Rubisco capacity which favoured photosynthesis and thus alleviated salt effect on biomass production (Lakhdar et al. 2009). Soil treatment with PM and OMWC significantly improved the soil chemical environment by increasing the cation exchange capacity (CEC) and soluble and exchangeable- K^+ contents and thus limited entry of Na^+ into the exchange complex. The K^+ and P supplied by these amendments also accounted for better crop nutrition and growth (Walker and Bernal 2008). Measurements of soil microbial biomass (SMB) and soil respiration rate indicated that organic matter incorporation in a saline-sodic soil significantly improved the cumulative soil respiration and SMB in comparison to both gypsum application and control treatments. Poor soil respiration and SMB in degraded soils were due to their low soil organic carbon levels. Following organic material input, an increase in SMB levels and respiration rates suggested that a dormant population of salt-tolerant SMB is present in these soils, which has become adapted to such environmental conditions over time and multiplies rapidly when substrate is available (Wong et al. 2009). These findings are ample to prove that the use of organic amendments can mitigate the salt stress in plants in an economical and environment-friendly way. Many easily available and low-cost industrial by-products such as press mud and distillery spent wash significantly improve the soil properties and crop yields in sodic soils. Press-mud application and wheat residue incorporation gave the highest rice and wheat yields in soils irrigated with high RSC (8.5 me l^{-1}) water (Yaduvanshi and Sharma 2007). Similarly, combined use of press-mud (10 Mg ha^{-1}), FYM (10 Mg ha^{-1}) and gypsum (5 Mg ha^{-1}) significantly enhanced rice and wheat yields under continuous sodic irrigation (Yaduvanshi and Swarup 2005). Application of 50% distillery effluent along with bio-amendments was best in improving the properties of sodic soil and in improved germination and seedling growth of pearl millet (Kaushik et al. 2005). These results show that alternative amendments could partially replace gypsum in reclamation programmes. A number of polymer-based soil conditioners have also given encouraging results in degraded soils. They improve soil aggregate stability [67] and water permeability (El-Morsy et al. 1991; Wallace et al. 1986). Zeolite application improved water infiltration in a fine-grained calcareous loess soil (Xiubin and Zhanbin 2001). Ca-zeolite application decreased the surface runoff and soil displacement in sodic soils presumably due to reduced clay dispersion, improvement in soil aggregation and the subsequent increase in soil hydraulic conductivity (Liu and Lal 2012). These results indicate that zeolite and other such compounds can prove useful in alleviating stress conditions in degraded soils given that their interactions with other components of soil system and effects on soil microbes and plants are not harmful.

9.6 *Plant-Based Solutions for Salinity Mitigation*

The use of salt-tolerant crops and cultivars is desirable to sustain the gains from both salt-affected and reclaimed soils. There use can greatly reduce water and chemical amendment use in the reclamation programmes. Saline and sodic soils put under salt-tolerant trees and shrubs show marked improvements in physico-chemical properties after a few years (Sharma and Chaudhari 2012; Sharma and Singh 2015) which is attributed to gradual increase in organic carbon and nutrient contents, better water permeability, higher microbial activity and decrease in soluble salts and exchangeable Na+ (Mishra et al. 2003; Nosetto et al. 2007). Different tree and shrub species have been identified for raising plantations in salt-affected community lands. The promising species for sodic lands include *Prosopis juliflora*, *Acacia nilotica*, *Casuarina equisetifolia*, *Tamarix articulata* and *Leptochloa fusca* (Singh et al. 1994). In addition to long-term improvements in soil quality, such candidate species are also important from the carbon sequestration perspective and are valuable in alleviating fuel wood and forage shortages in rural areas (Sharma et al. 2014b). Fruit tree-based agri-horti systems (*Aegle marmelos*, *Emblica officinalis* and *Carissa congesta* as main components and cluster bean and barley as subsidiary components) have been identified for areas having marginal quality water (EC_{iw} 6–10 dS m^{-1}) (Dagar et al. 2008). A number of medicinal plants such as *Plantago ovata*, *Aloe barbadensis* and *Andrographis paniculata* perform and yield well under saline irrigation (Tomar and Minhas 2004). Rampant waterlogging and salinity in many irrigation commands have turned thousands of hectares of agricultural lands into barren tracts. Water seepage from canals, excess irrigation and drainage congestion induce water-table rise and salt accumulation in root zone (Chhabra and Thakur 1998). Traditionally, waterlogged lands are reclaimed by SSD. The slow penetration of SSD technology, however, due to prohibitive costs, difficulties in maintenance and environmental issues in drainage effluent disposal (Chhabra and Thakur 1998; Gupta 2002; Ram et al. 2011), has enhanced interest in bio-drainage through salt-tolerant trees (Ram et al. 2011). Bio-drainage involves the planting of salt-tolerant and fast-transpiring trees to pump out the excess water and dissolved salts. This bioenergy-driven technology has proved effective in arresting salinization process in irrigated lands when suitable tree species (e.g. eucalyptus, popular and bamboo) are raised in the beginning (Heuperman et al. 2002). In areas where dryland salinity is emerging as a major form of land degradation, as in southern Australia, planting of perennial trees, shrubs and pastures is suggested to lower the groundwater tables to arrest the process of salinity build-up (Schofield 1992). It is, however, observed that such revegetation plans are hindered by shallow water tables and high salinity in discharge zones. Again, the maximum reduction of water tables from revegetation in discharge areas is only about 2.5 m. These observations indicate usefulness of tree plantations for the localized salinity management in recharge areas (George et al. 1999). Concerted efforts over the past four decades have resulted in the development of promising salt-tolerant varieties in rice, wheat and mustard. These salt-tolerant varieties provide a viable and cost-effective solution to the resource poor farmers in saline environments by ensuring better and stable yields even with reduced doses or no use of amendments. These varieties also exhibit tolerance to climate variability-induced adverse soil conditions such as waterlogging. There is a growing realization, however, that exclusive focus on breeding for salt tolerance would no longer work and that the development of multiple stress-tolerant crop genotypes must be prioritized by integrating molecular and genomics tools with conventional breeding approaches (Sharma and Singh 2015). In India, the development of salt-tolerant rice varieties started in the 1940s.

Initially, varieties such as Pokkali and Jhona 359 were developed through selection from the locally adapted landraces under coastal saline and inland saline-sodic soil conditions, respectively. Systematic breeding efforts from the 1960s onwards, however, resulted in the development of many promising types for commercial cultivation (Singh et al. 2010). In spite of the availability of a number of improved selections, only a few have become popular among the farmers. The major reasons behind limited adoption by the farmers are low level of salt tolerance relative to the locally adapted landraces and poor grain quality (Singh et al. 2010). The recent trends in the development of salt-tolerant rice cultivars include greater emphasis on quantitative trait loci (QTL) mapping and marker-assisted breeding for introgression of markers tightly linked to the submergence tolerance gene (*SUB1*) and QTL for salinity tolerance at the seedling stage (qSALTOL) in the background of high-yielding cultivars (Singh et al. 2010).

9.7 *Saline Aquaculture*

Degraded land and water resources in salinity-affected regions can be put to profitable use by shrimp and fish farming (Purushothaman et al. 2014). Over the years, aquaculture using saline groundwater has emerged as a viable land-use practice in many saline tracts of Australia, Israel and the USA (Burnell and Allan 2009). Consistent with the national goals, as mentioned in the 11th Five-Year Plan of Indian Council of Agricultural Research, efforts have been made to demonstrate the practical feasibility of commercial fish culture in saline lands. Despite very high salinity of pond water (25 dS m^{-1}), limited water availability and high evaporative losses, better fish growth was observed (CSSRI 2013). Seaweed cultivation has also emerged as an attractive option to harness the productivity of poorly drained saline lands. Seaweeds are large, multicellular marine algae and constitute an important renewable resource in the marine environment (Subba Rao and Mantri 2006). They are eaten raw, cooked or processed and have applications in many cosmetic and pharmaceutical products as active ingredients (e.g. seaweed polysaccharides such as agars, carrageenans and alginates). Rising global demand for seafood and declining fish catches have also proved conducive to the growth of this sector (Neoria et al. 2004). Notwithstanding a long coastline (~8000 kms) and rich seaweed diversity, commercial seaweed cultivation is still in a nascent stage in India. Although large tracts of suitable areas are available, seaweed industry suffers from the absence of standardized practices, lack of infrastructure and the absence of policy support. In addition to economic use of saline lands, seaweed cultivation presents several opportunities such as carbon sequestration, provision of breeding grounds for fish and shellfish, pollution abatement and diversified uses as animal feed and fertilizers (NAAS 2003).

9.8 *Microbial Approaches for Salinity Mitigation*

Of late, the need to exploit the potential of salt-tolerant microorganisms to alleviate salt stress in plants has gained attention. Collectively referred to as plant growth-promoting rhizobacteria (PGPR), these soil microbes upregulate the levels of growth-promoting phytohormones, volatile organic compounds and extracellular enzymes and improve the availability of nutrients for enhanced tolerance to abiotic stresses (Ruzzi and Aroca 2015). As such soil microorganisms exhibit considerable salt tolerance and have potential to promote plant growth in saline and sodic soils (Arora et al. 2014), studies have been carried out to isolate and utilize effective strains in salinity management in different field and horticultural crops. Endophytic bacteria induced sodicity tolerance in polyembryonic mango rootstocks (GPL-1 and ML-2) which was presumably due to higher activity of extracellular enzymes such as amylase, protease, cellulase and lipase (Kannan et al. 2015). The physiological bases of salinity mitigation by these microorganisms include higher uptake of K^{+} ions, improvement in water absorption and leaf water relations, stability of chlorophyll pigments and increase in photosynthesis, elevated levels of antioxidant enzymes and expression of genes involved in salt tolerance (Ruzzi and Aroca 2015). Although effective in alleviating salt stress in crops, the use of microbial inoculants is limited due to higher costs and lack of technical know-how. To circumvent these constraints, a low-cost microbial bioformulation ‘CSR- BIO’, based on a consortium of *Bacillus pumilus*, *Bacillus thuringiensis* and *Trichoderma harzianum* on dynamic media, has been developed. It acts as a soil conditioner and nutrient mobilizer and significantly increases the productivity of crops like rice, banana, vegetables and gladiolus in sodic soils (Damodaran et al. 2013). Arbuscular mycorrhizal (AM) fungi mitigate the detrimental effects of salinity by regulating key physiological functions including the accumulation of compatible solutes to avoid cell dehydration, regulation of ion and water uptake by roots, reduction of oxidative stress by enhancing the antioxidant capacity and stabilizing photosynthesis for sustained growth (Ruiz-Lozano et al. 2012). Under salt stress (0.1–0.5% NaCl), AM-inoculated *Jatropha* plants had greater dry weight of shoots and roots, better leaf water status, low lipid peroxidation, higher osmotic adjustment and higher leaf chlorophyll concentrations than non-AM-inoculated plants (Kumar et al. 2010). Two AM strains *Glomus fasciculatum* and *G. macrocarpum*, alone and in combination, improved growth, development and mineral nutrition in salt-stressed *Acacia auriculiformis* plants (Giri et al. 2003). Arbuscular mycorrhizal fungi *Glomus mosseae* alleviated salt-induced reduction of root colonization, growth, leaf area, chlorophyll content, fruit fresh weight and fruit yield in tomato cultivar Zhongzha 105 under NaCl salinity (Latef and Chaoxing 2011). Red tangerine (*Citrus tangerine* Hort. ex Tanaka) seedlings inoculated with AM fungi (*Glomus mosseae* and *Paraglomus occultum*) had better shoot and root growth and produced significantly higher biomass under 100 mM NaCl salinity as compared to non-mycorrhizal controls. Inoculation with AM fungi significantly increased root length and root surface area, improved photosynthesis and reduced leaf Na^+ concentrations resulting in favourable ionic balance in terms of high $K+/Na^+$ ratio (Wu et al. 2010).

10. Emerging Constraints in Salinity Research

Evidence is mounting that climate change effects would be more severe in salt-affected environments. Changes in the current temperature and rainfall patterns would cause heavy production losses in arid and semiarid 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 agroecosystems (Yeo 1998). As most of the crops are salt sensitive, increase in temperatures would result in more evapotranspiration losses resulting in increased salt accumulation in foliage (Yeo 1998). Coastal aquifers across the world are experiencing enhanced ingress of sea water caused by both natural and anthropogenic processes. The problem seems to have reached critical levels in shallow aquifers located in the vicinity of coastline. Although precise quantitative estimates of the patterns of movement and mixing between freshwater and saline sea water are mostly unavailable, availability of such information is a prerequisite for designing the appropriate prevention and management practices to cope up with this challenge (Ranjan et al. 2006). In saline and sodic soils, existence of diverse stresses such as excess salts, anaerobic conditions, drought and boron toxicity adversely affects 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 is 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.

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 and Qureshi 2010). As severe water shortages are impacting agricultural production in many parts of the world, water-starved arid and semiarid lands having salt-affected soils could be worst affected (Williams 1999). Good quality water availability in desired quantities is of utmost importance for higher agricultural productivity. Besides continuous decrease in the availability of freshwater resources, many parts of India suffering from water scarcity are also usually underlain by poor quality aquifers (Singh 2009). Research priorities have been outlined to standardize the protocols for the use of polluted waters in reclamation, and significant achievements have been made with respect to groundwater recharge, storage and subsequent use of rainwater through land modification and other technological interventions such as *dorouv* technology to skim fresh water floating on the saline water (Shrama et al. 2014a). The disposal of saline drainage water containing toxic salts and pollutants (Heuperman et al. 2002) into rivers, lakes and seas is neither environmentally acceptable nor economically viable in inland regions. Again, localized disposal may adversely affect the soil and environmental health (Tanji and Kielen 2002; Tripathi et al. 2008). The use of evaporation ponds to dispose such drainage effluents suffers from higher establishment costs and specific design requirements (Tripathi et al. 2008). It thus becomes imperative to utilize the drainage water at the place of origin. The prospects of using drainage water in irrigation are maximized when a source of fresh water is also available so as to use saline water in cyclic and/or blending modes with good quality water (Shennan et al. 1995). Selection of appropriate salt-tolerant crops and varieties would be a key to the success of conjunctive water use (Grattan et al. 2004). Pre-sowing irrigation with fresh water and subsequent use of saline and fresh water in alternate/blended modes have given good results in wheat (Sharma and Rao 1998), and further refinements are being made to widen the scope and practical utility of this technique in other crops. Besides widespread secondary salinity in irrigated lands, growing instances of resodification (Gharaibeh et al. 2014; Tripathi and Singh 2010) and resalinization (Amin 2004; Valipour 2014) of the ameliorated soils have caught attention. Reclaimed soils support agricultural production for a few years and gradually attain their original state. The adverse conditions which favour reappearance of sodic and saline patches include drainage congestion and shallow water tables (Buckland et al. 1986), canal seepage and subsequent waterlogging (Shakya and Singh 2010), repeated droughts (Fekete et al. 2002) and practice of crop fallow (Tripathi and Singh 2010). The agronomic 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 should be adopted to ensure lasting returns from the reclaimed soils (Sharma et al. 2014a).

11. Conclusion and Future Thrust

The food and nutritional security of the burgeoning world population faces a number of formidable challenges such as land degradation, freshwater scarcity and climate change. Available evidences show that these problems are likely to aggravate in the future. It is thus imperative to augment the productivity of existing agricultural lands as well as to bring the abandoned lands under crop production in a socially acceptable and economically viable manner. It is increasingly being realized that current food production and distribution systems have not been able to ensure the food and nutritional requirements of a large chunk of global population. The situation is particularly grim in many underdeveloped and developing countries where problems of salinity-induced land and water degradation have also risen substantially in the last few decades. Although significant achievements have been made to harness the productivity of saline lands, emerging constraints have necessitated a relook at research strategies to fine-tune them to the current and emerging challenges.

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