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Role of ICAR-CSSRI in sustainable management of salt-affected soils—achievements, current trends and future perspectives

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SUMMARY

A range of constraints are adversely impacting the sustainability of agricultural systems across the world. While productive agricultural lands are being usurped by municipal and industrial sectors of the economy, freshwater resources face heavy risks of depletion and pollution. Adverse impacts of climate change on soil health, water availability and crop productivity are increasingly becoming noticeable. Given the fact that both prime land and water resources have shrunk over the years, it has become absolutely essential to harness the productivity of degraded lands and low-quality water to meet the growing food and nutritional needs of an expanding global population. Salt-affected soils constitute a significant proportion of global degraded lands; especially in arid, semi-arid and coastal regions where poor-quality saline and sodic water are also a severe obstacle to sustainable crop production. The ICAR-Central Soil Salinity Research Institute (CSSRI) has made earnest efforts since the beginning to address these challenges, to bring degraded and abandoned agricultural lands under crop production. Different salinity-management technologies have become highly popular among the farmers in salt-affected regions of the country. Concerted research efforts are underway to devise novel and low-cost interventions for increasing farmers' income in saline-affected environments. In this paper, a summary of past breakthroughs, latest developments and emerging constraints is critically analyzed to delineate the future course of action for sustainable salinity management in agriculture.

The role of modern technology in contemporary agricultural development is well established. In fact, modernization of agriculture in the large parts of the developing and underdeveloped countries in the second half of 20th century was essentially a manifestation of the improvements brought about by the technological change during the Green Revolution period (Pinstrup-Andersen and Hazell, 1985). The huge success of Green Revolution in Indian subcontinent and many parts of Africa is a testimony to the fact that adoption of improved production technologies improves the soil conditions, enhances the crop production and ensures handsome returns to the farmers (Varshney, 1989, Goldman and Smith, 1995; Niazi, 2004; Swaminathan, 2006). A blend of strategically chosen technologies—productive cultivars, chemical fertilizers, farm machinery and irrigation—transformed the agrarian landscapes in many parts of Asia and Africa, alleviating hunger and poverty risks and bringing significant improvements in the lives of rural poor (Goldman and Smith, 1995). Besides direct benefits in terms of high crop yields, technological innovations also ensured less drudgery and high returns to the human labour employed in farm operations (Giampietro, 1994). These technology-led improvements in soil productivity also implied that pristine and protected environments will not be encroached for the agricultural expansion (Niazi, 2004).

Despite huge contributions in augmenting crop production in many historically disadvantageous regions of the world, Green Revolution is often criticized for being insensitive to environmental sustainability (Singh, 2000; Lynch, 2007) and human health (Welch and Graham, 1999; Welch, 2002) concerns. While criticizing the contributions of GR towards enhancing the agricultural output, commentators ignore the fact that the problems of widespread hunger and starvation, especially in poor countries where GR took place, could have attained alarming proportions had there been no provision of high-yielding crops and other essential inputs to augment the crop productivity (Welch and Graham, 1999). The eventual impact of any external intervention is greatly influenced by the prevailing policy environment. A given technology is likely to give the best results under favourable working conditions that can be ushered through institutional reforms. While implementing such changes, it is important to remember the fact that quest to improve agricultural productivity through modern tools must be in sync with the larger social and environmental goals (Pinstrup-Andersen and Hazell, 1985). The proponents of GR never imagined the widespread ill-use of the prescriptions originally meant to overcome the food shortages by harnessing the productivity of fertile but underutilized crop lands. It

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is argued that by augmenting per unit crop productivity, GR technologies saved the precious wildlife and protected lands which could have been usurped for agricultural use (Niazi, 2004). Based on these facts, it seems correct to state that even during the early years of GR individual commercial motives far outweighed the sustainability concerns posing a grave threat to the ecological health in the ensuing decades (Swaminathan, 2006).

INTENSIVE CROPPING AND AGRICULTURAL SUSTAINABILITY

Based on the recent trends in food production, Welch and Graham (1999) discerned 2 distinct phases of technology-driven agricultural development in Afro-Asian countries in the second half of 20th century. The first phase, aptly referred to as '*production paradigm*' started in 1960s and was characterized by the use of fertilizer-responsive cultivars, intensive irrigation and farm mechanization to sustain the rising global food demands. Although agricultural intensification ensured quantum increases in the production of staple crops such as rice (*Oryza sativa* L.) and wheat [*Triticum aestivum* L. emend. Fiori & Paol.], it soon became evident that intensive cropping was detrimental to natural-resource sustainability and environmental integrity. Over the years, environmentalists started questioning the validity of GR practices that were perceived to be inimical to land and environmental health. Thus emerged the second phase called '*sustainability paradigm*'. Institutionalized in early 1980s, it was steered by the consideration that agricultural production and natural resource sustainability were inextricably linked domains and that future interventions to increase crop production must be compatible with the environmental ethos and needs of local communities that are likely to benefit from such actions. Dawn of the 21st century marked an increasing global attention on rampant malnourishment necessitating a '*new paradigm*' in agricultural production to devise the means and ways that can foster the balanced nutritional needs of a rapidly expanding global population, especially the marginalized sections of society, while ensuring the ecological balance (Pinstrup-Andersen and Pandya-Lorch, 1998; Welch and Graham, 1999).

After Independence, India faced a daunting challenge to feed her vast poor population. The food availability was critically low such that a large chunk of population faced extreme hardships in securing access to food even for subsistence needs. The fact that agricultural production was largely rainfed implied that adequate rainfall would determine the farmers' fortunes. It was due to this reason that droughts or prolonged dry spells caused severe food scarcity and starvation. In a dramatic turnaround, food production considerably increased—from 72.3 million tonnes in 1965–66 to 108.4 million tonnes in 1970–71. By any standard, it was an impressive gain transforming a net food importing country into a food surplus economy. Considering the flaws in traditional strategy involving land reforms and cooperative agriculture, Government of India made some outright changes in policy to usher in a yield revolution through technological interventions and policy initiatives in a short span of 3 years, i.e. from 1964–1967 (Varshney, 1989). During the last years of 1960s and throughout 1970s, sustained efforts were also made to remove policy obstacles and market distortions to encourage the farmers to grow more food with the aid of improved seeds and other essential inputs (Jha *et al*., 2007).

Semi-dwarf wheat and rice cultivars having tolerance to lodging were far responsive to irrigation and fertilizers than the traditional tall cultivars. The high yield potential of these improved cultivars was evident right since the beginning, i.e. around mid-1960s when the field demonstrations started in north-western states such as Punjab. Subsequent to their release, dramatic improvements in crop productivity occurred with lands earlier considered to be less productive now producing exceptionally higher yields. Shortly, it appears, farmers developed the idea that yield potential of these 'miraculous seeds' can be further enhanced by the incremental additions of nutrients and water. As a consequence, over-irrigation and indiscriminate fertilizer use became a rule rather than exception—a practice which even continues today. Swaminathan (1968, 2006) noted that imprudent nutrient and water-management practices had become pervasive well before the term Green Revolution itself was coined by Dr William Gaud of the US Department of Agriculture in 1968. Taking a note of the fact that over allocation of water, neglect of land drainage, heavy fertilizer and pesticide applications, frequent soil tilling, excessive withdrawal of fresh groundwater and replacement of local crops with high-yielding cultivars have become a norm in many irrigated lands of north-western India, he cautioned about the dire consequences of these practices way back in January 1968 (Swaminathan, 2006).

PRECAUTIONS IN TECHNOLOGY ADOPTION AND IMPLEMENTATION

The key message emerging from the foregoing discussion is that while technological interventions are necessary to address the shortfalls in agricultural productivity, utmost care should be taken to ensure that a particular technology (e.g. irrigation) is not indiscriminately used, as it may prove detrimental to agro-ecosystem sustainability in longer runs. The fact that dwarf wheat and rice cultivars used during GR gave the best results under optimal soil moisture and nutrient conditions was mistaken by the farmers' who wrongly assumed that heavy and repeated use of such crop inputs will keep increasing the grain yields. Pingali and Rosegrant (1994) argue that GR strategy in Asia essentially aimed at the intensive use of lowlands for long-term gains in rice productivity. Efforts to harness the productivity of such lands also implied lesser pressure on overstretched uplands, consistent incomes to the growers and the creation of rural employment opportunities. Initially, GR technologies seemed to be an appealing proposition to enhance the land value and strengthen the livelihoods of resource-poor farmers. However, stagnant and/ or declining rice yields by the mid-1980s questioned the lasting relevance of this approach. Besides volatility in global rice demands and prices, the intensification-induced factors such as repeated pest outbreaks, soil-nutrient depletion and massive land degradation emerged as severe problems, impacting the land sustainability and farmers' livelihoods in most of the lowland rice ecosystems.

Considering the extent of public investments and the nature of policy support, Pingali (2012) distinguished the first GR (1965–85) from the second or post-GR (1986–2005). While the first leg witnessed heavy public investments in crop breeding and irrigation infrastructure development and was characterized by a congenial policy environment, public support gradually diminished and virtually came to a halt in mid-2000s that, according to him, marked the end of GR era. It was an unwelcome development as declining public support can impede the future productivity gains in many poor and underdeveloped regions where agriculture still continues to be the main driver of economic growth. The success of GR in terms of higher yields, improvements in farmers' livelihoods and poverty reduction in countries that suffered from some of the devastating famines in the past was, by any standard, remarkable (Niazi, 2004). Fifty years down the line, many countries that witnessed immense growth in agricultural production during GR have become victims of many unintended side-effects that remain unaddressed (Hazell, 2009). In spite of these shortcomings, technology-based reforms are still considered important, albeit with caution, to ensure the food and nutritional security of a burgeoning global population in a sustainable manner through innovative approaches variously described as Sustainable Intensification of Agriculture (Tilman *et al*., 2011), Second Green Revolution (Lynch, 2007), Evergreen Revolution (Swaminathan, 2006), Redux Green Revolution (Pingali, 2012) and Gene Revolution (Raney, 2007).

AGRICULTURAL INTENSIFICATION, LAND DEGRADATION AND SALINIZATION

Numerous studies show that the human quest to produce more food for commercial motives has come at the expense of massive land and environmental degradation in many parts of the world (Matson *et al*., 1997; Vitousek *et al*., 1997; Tilman *et al*., 2002; Sharma and Singh, 2015). Intensive cultivation-induced erosion of fertile soils (Pimentel *et al.*, 1995), fast diminishing crop biodiversity (Benton *et al*., 2003), rampant surface water pollution (Stoate *et al*., 2001), deterioration in groundwater quality (Gregory *et al*., 2002) and massive salinity build-up in agricultural lands (Gupta and Abrol, 2000; Singh *et al*., 2012) are some of the well-documented examples that reveal the enormous damage caused by the water- and energy-intensive agricultural practices.

Rice and wheat crops together contribute about 45% of the digestible energy and 30% of total protein to the global human diet. Rice and wheat are grown in sequence on the same land in the same year over 26 million ha area in South and East Asia and in about 12 million ha in India (Gangwar *et al*., 2006). Unfortunately, heavy tillage and other intensive practices have caused severe erosion of fertile soils in the Indo-Gangetic plains of India synonymous with the rice–wheat cropping system (RWCS) (Singh *et al*., 1992). The realization that business as usual approach adopted since the GR days has become irrelevant in the changing scenario has necessitated the adoption of resource-conservation technologies—reduced tillage, innovative crop establishment methods, crop residue incorporation, efficient irrigation techniques and integrated nutrient management—to address the interrelated concerns of soil degradation, sustainability and profitability of RWCS for national food security (Gupta and Seth, 2007).

Continued reliance on a set of high-yielding cultivars in RWCS has accelerated genetic erosion leading to the disappearance of many locally adapted landraces which were earlier integral parts of human diets in different regions (Singh, 2000; Gupta *et al*., 2003). Biodiversity depletion disrupts many ecosystem services and causes the loss of valuable genetic stocks important for future crop improvement. Water has been a key driver of agricultural growth in the country. However, it is distressing to note that both surface and groundwater resources are facing heavy pollution risks. The alarming deterioration in water quality is evident by the fact that presently over 70% of the available surface water suffers from different organic and inorganic pollutants to varying degree. Again, toxic levels of water-soluble salts and minerals such as iron, fluoride and arsenic have been reported in groundwater from over 200 districts in 19 states of India (Murty and Kumar, 2011).

Massive salinization of agricultural lands is one of the most important facets of intensification-induced environmental degradation. Human-induced secondary salinization of soils has emerged as a severe environmental crisis in many irrigated and dryland regions of the world. Excess water and salt accumulation in root zone adversely impact the productivity of about 20% global irrigated lands (Munns, 2005). Over-irrigation and neglect of drainage lead to permanent water stagnation in cultivated soils turning them into wet deserts (Pimentel *et al*., 2004). This is the case with the Indo-Gangetic plains of Indian subcontinent where twin menaces of waterlogging and salinity have dealt a serious blow to agricultural sustainability and farmers' livelihood (Datta and De Jong, 2002; Bhutta and Smedema, 2007; Sharma and Singh, 2015). Under severe conditions, virtually no crop can be produced in the waterlogged soils leading to their abandonment (Singh and Singh, 1995). In most of the cases, formation of such damp soils is ascribed to the deep-rooted flaws in irrigation-development schemes that tend to ignore the importance of adequate drainage for sustainable land use (Janmaat, 2004).

As previously indicated, attempts to bring more and more lands under irrigation through the development of canal networks and establishment of tubewells at farmers' field was a key strategy during the GR period. Many a times, farmers' facing the problem of erratic supplies of canal water became overly dependent on groundwater irrigation. Initially, this approach proved useful in tackling the twin problems of waterlogging and secondary alkalization as well as in accelerating the speed of alkali soil-reclamation programmes in regions, having good quality groundwater. The gradual spread of RWCS in these areas, however, markedly changed the natural salt and water balance such that north-eastern parts of Punjab and Haryana states started showing decline in groundwater table while, the south-western parts developed many extensive pockets of secondary salinization (Gupta and Abrol, 2000). Based on a long-term study (1989–2010) in Haryana state of India, it was found that percolation from irrigated soils was mainly responsible for the development of shallow watertables with annual rate of groundwater rise being as high as 0.2 m in some locations. Some viable options to arrest the continuous rise in watertable include the conjunctive use of groundwater and canal water and reduction in rice area by adopting low-water-requiring crops (Singh *et al*., 2012).

Most of the aforementioned problems are likely to aggravate in the coming decades. Continued demographic expansion implies that intensive land-use practices may become more widespread with far reaching consequences. Although agricultural intensification has considerably increased the global crop harvests, it has come at the cost of unintended impacts on vital ecosystem services and functions (Matson *et al*., 1997). It is argued that the need to double global food production in the next few decades may prove detrimental, causing irreversible damages to soil, water and biodiversity resources imperative for and integral to sustainable human life on Earth (Tilman *et al*., 2002). The poor and developing countries such as those in south Asia may be worst affected by these unwarranted challenges that are likely to be further complicated by the global environmental change (i.e. changes in biophysical environment caused by the anthropogenic activities). Some of the major challenges that lie ahead include pervasive land use, extreme climate events, freshwater shortages and biodiversity loss. The extreme vulnerability of south Asian countries to such challenges is attributed to an apparent lack of technological and material resources necessary for effective adaptation (Aggarwal *et al*., 2004).

JUSTIFICATIONS FOR INVESTMENTS IN SOIL-RECLAMATION PROJECTS

The twin problems of salinity and waterlogging have impacted agricultural production in arid areas since the inception of human civilization on Earth. In recent times, however, they have grown in propensity and increasingly threaten the sustainability of agriculture in different irrigation schemes across the world (Wichelns and Qadir, 2015). The problem of dryland salinity has also emerged as a formidable threat to sustainable crop production in many rainfed regions such as southern Australia (Lambers, 2003; Munns, 2005). One recent estimate revealed that salinity-induced global annual losses in agricultural production (about US $12 billion) may substantially exceed in the next few decades if efforts are not made to mitigate the salt stress in crop lands (Shabala, 2013). Appropriate technological interventions ensure handsome returns from the ameliorated soils that will otherwise remain unutilized. Although large-scale public investments in technology development and dissemination remain crucial, efforts by individual farmers or their co-operatives also bring significant improvements in the productivity of degraded lands. Successful demonstration of a given technology in the field proves catalytic to its adoption by the farmers. Once the farmers are convinced that a technology holds promise to address the problem, they make investments to reap the potential benefits (Sharma and Singh, 2015). These facts justify the need to invest in innovative salinity-management technologies. Global trends reveal that many research and development organizations are developing international linkages to accelerate the pace of salinity research. In the past few years, collaborations between public and private sectors have also significantly increased to develop cost-effective and environmental-friendly solutions for salt-stress alleviation (Rozema and Flowers, 2008).

While both prime lands and good-quality water resources are shrinking with time, degraded salt-affected soils (SAS) offer ample scope for agricultural expansion into marginal environments. Although vast tracts of SAS are seen as a bane to society, evidence is mounting that they can be transformed into valuable assets by investments in technology development and dissemination (Shukla and Misra, 1993). In particular, emphasis should be on the development of low-cost technologies to minimize the resource-poor farmers' dependence on costly external inputs (Sharma and Singh, 2015). Technology-driven productivity enhancements are particularly desirable in those regions where significant investments have already been made in irrigation and drainage infrastructure. Precise mapping of salt-affected lands is one of the pre-requisites for their utilization through strategic land-management plans. Availability of accurate information with respect to the severity of the problem is extremely valuable in adopting a context-specific soil-restoration technology. For example, moderately saline and sodic soils will require less investment to bring them into use than a highly degraded soil. Besides the extent of salt-affectedness, factors such as land topography, presence of hard subsoil, water quality, depth of groundwater and crops to be grown after reclamation significantly affect the cost of technological interventions (Qadir *et al*., 2014).

ROLE OF ICAR-CSSRI IN PRODUCTIVITY ENHANCEMENTS OF SALT-AFFECTED SOILS

It may be a mere coincidence that ICAR-Central Soil Salinity Research Institute (CSSRI) was established in 1969—a time when the initial impacts of GR technologies were becoming noticeable. The establishment of ICAR-CSSRI marked a two-pronged strategy of agricultural development by the Indian Government. While on one hand technological changes and policy initiatives were initiated to boost the productivity of fertile yet low-yielding soils, on the other there was an increasing emphasis on tapping the potential of degraded, SAS. Although attempts were also made in the past to bring marginal soils under crop production, most of them were temporary provisions and thus tangible improvements did not materialize. The realization that systematic researches were necessary to identify the causes of salinization for designing the effective remedial measures led to organized salinity research in India.

Besides the investigations being carried out at the headquarters at Karnal, 3 Regional Research Stations have also been established at Canning Town, West Bengal (February 1970), Anand, Gujarat (February 1989; subsequently relocated to Bharuch) and Lucknow, Uttar Pradesh (October, 1999), to study the causative factors and to develop appropriate solutions for the problems of coastal salinity, inland salinity in black soils region and alkali lands of Indo-Gangetic plains, respectively. In addition, All India Coordinated Research Project on Management of Salt Affected Soil and Use of Saline Water in Agriculture started during the Fourth Five-Year Plan under the aegis of Indian council of Agricultural Research, New Delhi also assists in salinity research through its adjunct centres located in different parts of the country (ICAR-CSSRI, 2015).

Since the beginning, it has been our constant endeavour to develop farmer-friendly technologies for the best productive utilization of SAS and poor-quality waters with greater focus on fragile agro-ecosystems in arid, semi-arid and coastal regions (Sharma and Singh, 2016). The Institute has developed a number of doable, critically acclaimed technologies for assured returns even from difficult-to-reclaim salt-affected lands across the country. Till date, over 2 million ha salt-affected area has been reclaimed using these technologies. An account of these technologies summarizing their strengths, weaknesses and impacts in farmers' fields are discussed under the following heads:

Gypsum-based reclamation of sodic lands

Gypsum is a widely used amendment for reclaiming the sodic soils having structural problems and impeded water flow. Gypsum treatment markedly improves soil physical conditions, as evident from better soil flocculation, aggregate stability and improved infiltration rate (Lebron *et al*., 2002). Alleviation of sodicity depends on the replacement of exchangeable Na^+ with Ca^{2+} by the addition of amendments such as gypsum ($CaSO_4.2H_2O$) and lime ($CaCO_3$) (Oster and Frenkel, 1980). Although lime ($CaCO_3$) is naturally found in majority of the sodic and saline-sodic soils of the world, it is sparingly soluble in water (0.0113%) and hence does not contribute to reclamation (Qadir *et al*., 1996). In contrast, high solubility of gypsum in water (0.26% at 25°C) makes it an effective reclamation agent (Hira and Singh, 1980). Addition of gypsum releases much higher quantities of Ca^{2+} than does an equivalent amount of lime (Oster and Frenkel, 1980). Although certain acids and acid-forming materials can solubilize the native $CaCO_3$ to supply adequate Ca^{2+} for the soil reclamation, high initial costs and safe-handling issues limit their potential applications (Qadir *et al*., 1996). Factors such as composition of the soil solution, temperature, gypsum fineness, hydraulic conductivity and original exchangeable Na^+ percentage (ESP) affect the dissolution of gypsum in sodic soils (Hira and Singh, 1980). When present in excess amounts in the form of large crystals, gypsum may prove detrimental to soil structure, as observed in many gypsiferous soils containing 10–35% gypsum (Al-Barrak and Rowell, 2006). Certain practices may enhance the efficiency of gypsum application in sodic soils. In Australia, for instance, deep tillage in gypsum-treated soils enhances its reclamation efficiency by hastening the water flux and salt leaching. In comparison, deep tillage without gypsum application often causes slumping and re-settling of soil (Hulugalle *et al*., 2010).

In India, sodic-soil reclamation has become virtually synonymous with the gypsum-based technology developed by the ICAR-CSSRI. Although an array of amendments such as gypsum, pyrite, sulphuric acid, nitric acid, aluminium sulphate, ferrous sulphate, pressmud and organic manures have been tested in sodic soils, only gypsum and pyrite have emerged as practically feasible amendments owing to their easy availability and low cost. Again, many field investigations have demonstrated the superiority of gypsum over pyrite as even a single application of gypsum before rice planting provs as effective as higher and repeated doses in the subsequent years. Although actual amount of gypsum to be applied depends on different factors, 10–15 tonnes gypsum proves sufficient to reclaim the upper 15 cm soil in 1 ha area for growing shallow-rooted crops such as rice, wheat, berseem or Egyptian clover (*Trifolium alexandrinum* L.) and barley (*Hordeum vulgare* L.) (Dagar, 2005). Over the past few decades, chemical amelioration of alkali soils in Indo-Gangetic regions of Punjab, Haryana and Uttar Pradesh has been well standardized. With the support of World Bank, European Union and other developmental agencies, India has reclaimed 1.95 million ha of alkali lands. Among sodicity affected states, Punjab has reclaimed the largest area (0.80 million ha), followed by Uttar Pradesh (0.73 M ha) and Haryana (0.35 million ha) (Sharma *et al*., 2016b). Although it is a proven technology, gypsum-based package has some implicit limitations. For example, it is increasingly becoming evident that agricultural-grade gypsum may not be available in required amounts in the future. Such a situation has enhanced the interest in easily available and least-priced amendments such as organic manures, pressmud and distillery spent wash. The initial results reveal that these low-cost amendments could partially substitute gypsum in future reclamation programmes (Sharma and Singh, 2015).

Sub-surface drainage of waterlogged saline lands

The history of world agriculture is replete with examples that reveal the importance of irrigation in sustaining the human food requirements since antiquity. It appears that even the ancient hunter gatherer societies knew the benefits of irrigation that allowed them to grow crops for a settled life. Besides depending on forest produce and animal meat for daily calorie needs, Indus valley people also cultivated the winter-season crops such as wheat and barley with the aid of irrigation. As crop production was not possible without assured water supplies, creation of the permanent sources of irrigation was indispensable (Chew, 1999). In medieval periods, the realization that irrigation enhances the soil productivity led to the creation of many canal networks by the Tughlaq and Mughal rulers during 14th and 15th centuries (Shahare *et al*., 2002). Arrival of British in India marked a new phase of irrigation development in the country. The colonial rulers were firmly convinced that irrigation development was a key to revenue generation in agrarian economies like India. Britishers saw irrigation as a ‘high input-high output enterprise’ and made heavy investments for expanding the canal irrigation. Many big ticket projects were also initiated to restore the canals that were in a state of despair (Shah, 2011). After country’s partition in 1947, large irrigated areas became part of Pakistan requiring focussed action to develop irrigation infrastructure in independent India. Thus, special programmes were launched through a series of different five-year plans up to the 1990s to install a number of major irrigation projects. Presently, 1,248 major and medium irrigation schemes are operational in the country. It is pertinent to mention that while there was almost an equal emphasis on surface and groundwater development in the decades of 1960s, 1970s and 1980s, there was a sizeable increase in groundwater development in the last three decades partly because of subsidized electricity for water pumping (Gopalakrishnan and Kulkarni, 2007).

This account of irrigation development reflects only one side of the story. While creating the new sources of irrigation, least attention was given to ensure proper drainage to obtain sustainable results in terms of multiple cropping, high crop yields, generation of rural employment and increase in the land value (Gopalakrishnan and Kulkarni, 2007). Presently, salinity affects the productivity of about 2.95 million ha agricultural lands in the country. Although precise estimates regarding irrigation-induced and groundwater-associated salinities are not known (Sharma *et al*., 2016a), the problem is on rise and is adversely impacting the soil health and crop production in many regions of the country (Datta and De Jong, 2002; Gupta, 2002; Manjunatha *et al*., 2004; Ritzema *et al*., 2008). Assessment of salinity-induced production and monetary losses by ICAR-CSSRI revealed that total production losses at the national level (~5.66 million tonnes) resulted in a revenue loss of about ₹8,000 crores. Among the salinity affected states, the highest losses have been reported from Gujarat, followed by Maharashtra and West Bengal (Sharma *et al*., 2016a).

In such wet soils, water table remains 1.5–2.0 m below the soil surface. Besides high salt concentrations [saturation extract salinity (EC_e) above 4 dS/m at 25° C], plants also suffer from osmotic stress and limited oxygen supply to the roots that eventually prove detrimental to crop growth and yield. Chlorides and sulphates of Na^+, Ca^{2+} and Mg^{2+} are the predominant soluble salts in these soils. The ICAR-CSSRI, Karnal, in collaboration with the Netherlands has standardized the subsurface drainage (SSD) technology for the reclamation of waterlogged saline soils. In SSD system, perforated corrugated/ smooth PVC pipes are installed manually or by laser-controlled trencher machines mechanically at a desired design spacing and depth below soil surface to drain out the excess water and soluble salts from the affected area. These pipes are covered with gravel/ synthetic filter to prevent the clogging (Gupta, 2002; Sharma *et al*., 2016a). Success of a few manually laid pilot SSD projects during 1980s proved conducive to the commissioning of many large, mechanically installed projects in the states of Haryana, Rajasthan, Maharashtra, Karnataka, Gujarat, Punjab and Andhra Pradesh. Thanks to the availability of adequate funds under different government-sponsored schemes and the entry of private companies in a public–private partnership mode, key installation and operational constraints have been overcome resulting in fast spread of SSD technology in many salt-affected regions. Till date, about 66,500 ha waterlogged saline soils have been reclaimed with SSD in India (Table 1; Sharma *et al*., 2016a). The reclaimed soils exhibit marked improvements in soil health, crop productivity, cropping intensity and overall environmental quality (Sharma and Singh, 2015).

Despite these benefits, smooth establishment and operation of SSD projects suffers from constraints such as high-installation costs and the lack of farmers' active involvement in the maintenance and running of SSD sites (Ritzema *et al*., 2008). Again, in many cases, problems encountered in the safe disposal of saline drainage water hamper SSD adoption in the landlocked regions. A range of solutions have been recommended to overcome these obstacles. They include provision of evaporation ponds, bio-drainage, conjunctive use of fresh and saline water in irrigation and the use of salt-tolerant cultivars. Of these approaches, the last 3 have received considerable attention to enhance the acceptability of SSD technology at farmers' fields.

Biodrainage for watertable control

Many tree species exhibit high transpiration rate and thus have capacity to extract water from the deeper layers containing saline groundwater. Experimental results show the efficiency of such trees in water and salt removal under shallow watertable conditions. *Eucalyptus* trees removed about 53% of the highly saline water (12 dS/m) vis-à-vis control conditions and thus arrested salinity development in the root zone (Chhabra and Thakur, 1998). Strip plantations of *Eucalyptus tereticornis* Sm. prevented the development of shallow watertables and salinity, while adjacent fields lacking tree cover recorded an upward movement of water (Ram *et al*., 2007). Raised bed plantations of *Eucalyptus camaldulensis* Dehnh., *E. Fastigata* H. Deane & Maiden, *E. rudis* Endl. and *Corymbia tessellaris* K.D. Jo;; & L.A.S. Johnson decreased the groundwater level and salinity in an alkali soil (*p*H 8.4–9.1). Groundwater level decreased by 145 cm under *E. rudis* trees compared to 90 cm, 70 cm and 60 cm in *C. tessellaris*, *E. camaldulensis* and *E. fastigata*, respectively, over a period of four and half years. Based on overall performance in terms of growth, biomass production, transpiration rate and overall bio-drainage potential, *E. rudis* was identified as the best candidate tree for waterlogged soils of Indian Thar desert (Bala *et al*., 2014).

These observations tend to show the importance of different tree species in the productive utilization of soils having shallow watertable. This strategy is also suitable for difficult terrain and subsoil conditions characterized by poor fertility and low-water transmission. In most of the

Table 1. An estimate of area reclaimed by subsurface-drainage projects in different irrigation commands of India

State	Irrigation commands	Area (ha)
Haryana	Western Yamuna Canal, Bhakra Canal	10,000
Rajasthan	Chambal, Indira Gandhi Nahar Pariyojana	16,500
Maharashtra	Lift irrigation systyem of Krishna river; Neera canal command, uncommanded	3,500*
Karnataka	Upper Krishna, Tungabhadra, Malprabha, Ghatprabha	25,000*
Punjab	Sirhind Canal (South West Punjab)	2,500
Manual[1]	Andhra Pradesh (Nagarjuna Sagar, Krishna Western Delta); Gujarat (MahiKadana, UkaiKakrapar); Kerala (Acid sulphate soils); Assam (Tea gardens), Madhya Pradesh	3,000
Total		60,500

* In addition to the above Government-supported projects, SSD has been installed in more than 3,000 ha area each in Maharashtra and Karnataka by local farmers without Government support. [1]Small projects in different states.

cases, eucalyptus and popular are the preferred tree species for controlling watertable. Many other species such as *Salvadora, Tamarix* and *Prosopis juliflora* have also been found suitable for SAS. Either strip or block plantations of the recommended trees are suggested to intercept canal seepage. In contrast to SSD, it is a cost-effective approach and also does not involve regular monitoring to grow and maintain the tree plantations which are also significant from environmental (e.g., carbon sequestration) and economic (e.g. industrial demand of tree timber) perspectives (Singh *et al*., 2014).

Conjunctive use of saline and freshwater

As the disposal of saline effluents from SSD systems carries the risk of environmental contamination, the prospects of using drainage water in conjunctive mode with freshwater have been investigated. Saline drainage water (EC_{iw} 10.5–15.0 dS/m) was applied in alternation with canal water (EC_{iw} 0.4 dS/m) for irrigation of wheat crop in a sandy-loam soil. Rainy-season crops were not irrigated. The mean relative yield of wheat irrigated only with saline water was 74% of the yield with freshwater. First irrigation with canal water and the subsequent use of drainage water increased the yield to 84%. Cyclic irrigations with canal and drainage water resulted in 88–94% of the potential yields. Cyclic irrigations also did not cause any yield reductions in sorghum [*Sorghum bicolor* (L.) Moench] and pearl millet [*Pennisetum glaucum*)L.) R. Br.] crops (Sharma *et al*., 1994). Wheat yield reduced by 40% when saline drainage water (EC_{iw} 12 dS/m) was used for irrigation. Substitution of saline water with canal water at pre-sowing and first post-planting stages improved the seedling establishment, tillering and plant growth, resulting in yield improvements of 16–18% than continuous saline irrigation (Naresh *et al*., 1993).

In many arid and semi-arid regions, erratic canal water supplies necessitate irrigation with saline groundwater. The productivity of such soils can be significantly enhanced if saline water is effectively utilized to supplement the water supplies. It has been found that pre-sowing irrigation with normal water and remainder irrigations with saline water (EC_{iw} 8 dS/m) is practically feasible in wheat crop in such areas. Again, saline water (EC_{iw} 8-12 dS/m) can also be used to substitute at least 2 freshwater irrigations with nominal yield reductions in wheat (Chauhan *et al*., 2008). These findings reflect that conjunctive use of marginal quality and fresh water is possible in the winter season crops such as wheat. When freshwater is used at the sensitive-crop stages, yield reductions are minimal. This practice holds even greater significance in areas where rainfall is adequate to leach the salts accumulated in the previous season. Adoption of salt-tolerant varieties and agronomic practices such as manuring and mulching can further enhance the prospects of saline water use under such conditions.

Salt-tolerant varieties

As previously mentioned, a number of constraints have hindered the widespread adoption of gypsum-based package and SSD at farmers' fields. In particular, the problems caused by higher costs (e.g. purchase of amendment, installation of SSD) have necessitated the development of alternative strategies to harness the productivity of SAS in a cost-effective manner. Salt-tolerant crops and cultivars capable of growing in unreclaimed or partially reclaimed soils represent such a strategy. Salt-tolerant cultivars give stable yields and significantly reduce the need to apply amendments for enhancing the soil productivity (ICAR-CSSRI, 2015). Crop-improvement projects in the last 40 years have led to the release of different high-yielding and salt-tolerant cultivars in crops such as rice, wheat, chickpea (*Cicer arietinum* L.), Indin mustard [*Brassica juncea* (L.) Czernj & Cosson] and dhaincha (*Sesbania cannabina*) (Table 2). New genotypes of rice ('CSR 46'), wheat ('KRL 283') and Indian mustard ('CS 58') have been identified for release in the coming period. Many potential lines have also been identified for use as parents in crop improvement and/or for direct release as cultivars. Recognizing the necessity to promote crop diversification in salt-affected environments, research programmes have also been initiated to identify salt tolerant and high-yielding genotypes in fruit crops, viz. Mango (*Mangifera indica* L.), bael (*Aegle marmelos* Correa ex. Koen.), guava (*Pridium guajava,* L.), ber or Indian jujube (*Ziziphus mauriatiana* Lam.) and vegetables, viz. Tomato (*Solanum lycopersium* L.), okra [*Abelmoschus esculentus* (L.)

Table 2. Salt tolerant crop varieties developed by the ICAR-CSSRI

Crop	Variety
Rice	'CSR 10', 'CSR 13', 'CSR 23', 'CSR 27', 'CSR 30', 'CSR 36', 'CSR 43'
Wheat	'KRL 1-4', 'KRL 19', 'KRL 210' 'KRL 213'
Chickpea	'Karnal Chana 1'
Indian Mustard	'CS 52', 'CS 54', 'CS 56'
Dhaincha	'CSD 137', 'CSD-123'

Moench], capsicum (*Capsicum* sp.) and chilli (*Capsicum* sp.) crops. Although tangible success has been achieved in developing and disseminating salt-tolerant cultivars to the farmers' fields, the changing scenario has necessitated development of multiple stress-tolerant crops capable of growing in soils having two or more constraints (e.g., drought and salinity). In this regard, integration of frontier genomic tools such as marker-assisted breeding with conventional breeding is necessary to accelerate the pace of ongoing genetic improvement projects.

Land-shaping technologies

Unrestricted water and air flows, as found in normal soils, are essential for the optimum plant growth and development. Water-permeable soils are amenable to intensive land use and multiple cropping for assured returns to the farmers. A number of low-cost and simple earth manoeuvring techniques such as farm ponds and paddy-cum-fish model have been found practically feasible to enhance the value of waterlogged lands (Ambast *et al*., 1998). The twin advantages of land shaping include the prevention of surface-water stagnation in the wet season and the use of stored rain water for irrigation in the dry months. It is thus obvious that such soil-displacement techniques alleviate the severe problem of waterlogging in the rainy season and allow crop cultivation in the ensuing winter season; a practice that assumes significance for intensifying the land use in monocropped coastal saline soils (Mandal *et al*., 2013). Similar interventions in salinity-affected regions of Haryana and Uttar Pradesh have also shown encouraging results.

Presence of high residual sodium carbonate (RSC) in groundwater is considered unsuitable for agricultural crops. A study conducted at farmers' field in Kurukshetra district of Haryana indicated the potential of land-shaping practices in enhancing the productivity of high RSC water through aquaculture-based farming system. Renovation of the existing pond (0.4 ha area) for fish cultivation, creation of a nursery pond, creation of pond dykes to grow horticultural crops and neutralization of high RSC in water with gypsum considerably enhanced the returns from a land which was otherwise lying unutilized (Singh *et al*., 2014). At Nain Experimental Farm, Panipat, characterized by shallow, saline groundwater table, promising results have been recorded by the creation of farm ponds. Despite constraints such as low-water availability and severe salinity in the pond water (25 dS/m) fish growth was about 600–800 g in 1 year period (CSSRI, 2013).

Efficient irrigation techniques

Globally, irrigated agriculture uses about 75% of the total available water. The next 2 slots are occupied by the industrial and municipal sectors that consume roughly 20% and 5% of the global pool respectively (UNEP, 2002). Although it has rendered immense benefits to the human society, fresh water is increasingly becoming a scarce resource putting many crucial ecosystem services and human health at risk. Some of the factors that have aggravated the problem—ever-growing human population, relentless land conversions, increasing urban population and industrial development—are likely to become more damaging in the foreseeable future (Vörösmarty *et al*., 2010). Adverse impacts of climate change such as increase in temperature, low and erratic rainfall and reduced river flows are expected to fuel the growing water scarcity (Whitehead *et al*., 2009) and the limited water zones (e.g. arid and semi-arid areas) characterized by poor soils, salinity and dismal farmers' adaptive capacity can be worst affected by these changes (Sharma and Singh, 2015). Under these conditions, agriculture sector will have to increasingly rely on limited freshwater. In many cases, poor-quality water will be the only viable option for crop irrigation and soil-reclamation programmes (Qadir and Oster, 2004).

A set of crop- and soil-management strategies including the cultivation of low water-requiring crops, reduced irrigation frequency, adoption of water-use efficient micro-irrigation practices, use of salt-tolerant cultivars, conjunctive water use and the application of organic inputs are recommended to tide over the freshwater shortages (Minhas, 1996). Drip irrigation offers many advantages over conventional surface irrigation in terms of significant reductions in water use, simultaneous application of water-soluble fertilizers (fertigation) and the advantageous use of low-quality water. While using salt-affected water under drip irrigation, however, some changes in the routine practices (e.g. selection of salt-tolerant crops) become absolutely essential. As direct contact between the plant and saline water is avoided, drip irrigation significantly minimizes the salt-induced damage (Mmolawa and Or, 2000). In light of the fact that regular saline irrigation through drip may accentuate salt accumulation in surface soil, subsurface/ drip irrigation is recommended to push the salts into deeper soil, so as to minimize the damage to crop roots (Oron *et al*., 1999). In this method, water is placed below the soil surface at a water discharge rate similar to that of surface drip (Camp, 1998).

Another relatively new irrigation technique called deficit irrigation (DI), where irrigation is applied below the crop evapo-transpiration (ET_c) need, is becoming popular to economize water use in crops (Fereres *et al*., 2012). The DI could be of lasting relevance in the regions where rainfall is adequate to fulfil crop-water needs during certain critical stages; especially in fruit and vine crops (Fereres and Soriano, 2007). A shortcoming with this technique is that excess salts may accumulate even with the prolonged use of good-quality water. The DI in mandarin trees (*Citrus clementina* cv. 'Orogrande') at 50% of ET reduced water consumption by about 15% with no apparent decrease in fruit yield. Nonetheless, DI for 3 years even with normal water (EC_{IW} 1 dS/m) enhanced salinity in the root zone (Mounzer *et al*., 2013). Partial root-zone drying (PRD) is another such techniques in which irrigation is done in such a way that only half of the root-system is wet, while the rest remains dry (Sepaskhah and Ahmadi, 2010). One of the shortcomings of DI is that it requires prudent supervision to maintain the required soil-moisture status (Stoll *et al*., 2000).

Challenges ahead

The adverse impacts of climate change on agricultural production are increasingly becoming noticeable in different parts of the world. Most of the projected changes—rise in atmospheric temperature, sudden and heavy downpour, drying of streams and reduced water flows in rivers—can prove detrimental to agriculture in most of the arid and semi-arid tracts characterized by low soil fertility, predominance of saline aquifers and resource-poor farmers (Enfors and Gordon, 2007; Sharma and Singh, 2015). The problems of sea-water ingress and cyclonic storms have significantly increased in the last few years, posing threats to the sustainability of coastal soils (Yeo, 1998). High atmospheric temperature, evaporative loss of water and less rainfall are likely to accentuate salt accumulation in soil (Yeo, 1998). In the last few years, problems of resodification (i.e. reappearance of sodic patches in gypsum-amended soils; Gharaibeh *et al*., 2014) and resalinization of ameliorated saline soils (Valipour, 2014) have become widespread. Growing scarcity of freshwater will necessitate changes in the conventional soil-reclamation strategies where good quality is an indispensable input for salt leaching. In many cases, marginal quality water will be the only viable option for irrigation and soil amelioration (Oster, 1994; Qadir and Oster, 2004). Strong climate variability may lead to the emergence of multiple soil stresses that could prove lethal to even the salt-tolerant genotypes. Development of cultivars having tolerance to two or more soil constraints is thus becoming a priority in genetic improvement programmes (Sharma and Singh, 2015).

CONCLUSION AND FUTURE PERSPECTIVES

In light of the fact that productive agricultural lands and freshwater are diminishing with time, considerable attention has been paid to bring the marginal soils under agricultural production. Although conventional salinity-management practices have paid rich dividends, the emerging constraints have necessitated a paradigm shift from the business-as-usual approach to ensure consistent gains from the soil reclamation projects. In near future, precise salinity mapping will become more important to identify the lands having slight to moderate constraints so as to design low-cost interventions for their profitable use. An equal emphasis on developing alternative solutions is desirable to hasten the pace of reclamation, especially in areas still uncovered by the conventional technologies. As in past, strong research and academic collaborations with national and international partners will remain important to bring additional salt-affected lands under crops and vegetation in a speedy and cost-effective manner. The capacity building and skill development of different stakeholders—scientists, state officers and farmers—should be given renewed emphasis to upgrade their knowledge and skills for sustainable results in the future reclamation projects.

REFERENCES

Aggarwal, P.K., Joshi, P.K., Ingram, J.S.I. and Gupta, R.K. 2004. Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation. *Environmental Science and Policy* **7**: 487–498.

Al-Barrak, K. and Rowell, D.L. 2006. The solubility of gypsum in calcareous soils. *Geoderma* **136**: 830–837.

Ambast *et al.*

Bala, N., Singh, G., Bohra, N.K., Limba, N.K. and Baloch, S.R. 2014. Biodrainage for restoration of canal command waterlogged area in Indian desert. *Indian Forester* **140**: 462–467.

Benton, T.G., Vickery, J.A. and Wilson, J.D. 2003. Farmland biodiversity: is habitat heterogeneity the key?. *Trends in Ecology* and *Evolution* **18**: 182–188.

Bhutta, M.N. and Smedema, L.K. 2007. One hundred years of waterlogging and salinity control in the Indus valley, Pakistan: a historical review. *Irrigation and Drainage* **56**: 81–90.

Camp, C.R. 1998. Subsurface drip irrigation : A review. *Transactions of the ASAE* **41** : 1353–1367.

Chauhan, C.P.S., Singh, R.B. and Gupta, S.K. 2008. Supplemental irrigation of wheat with saline water. *Agricultural Water Management* **95**: 253–258.

Chew, S.C. 1999. Ecological relations and the decline of civilizations in the Bronze Age world system: Mesopotamia and Harappa 2500 **B.C.**- 1700 **B.C.** (In) *Ecology and the World-System*, pp. 265. Goldfrank, W.L. *et al*. (Eds). Greenwood Press, Westport, USA.

Chhabra, R. and Thakur, N.P. 1998. Lysimeter study on the use of biodrainage to control waterlogging and secondary salinization in (canal) irrigated arid/semi-arid environment. *Irrigation and Drainage Systems* **12**: 265–288.

CSSRI. 2013. *Annual Report, 2013–14*, Central Soil Salinity Research Institute, Karnal, Haryana, India.

Dagar, J. C. 2005. Salinity research in India: An overview. *Bulletin of the National Institute of Ecology* **15**: 69–80.

Datta, K.K. and De Jong, C. 2002. Adverse effect of waterlogging and soil salinity on crop and land productivity in northwest region of Haryana, India. *Agricultural Water Management* **57**: 223–238.

Enfors, E.I. and Gordon, L.J. 2007. Analysing resilience in dryland agro-ecosystems: a case study of the Makanya catchment in Tanzania over the past 50 years. *Land Degradation and Development* **18**: 680–696.

Fereres, E. and Soriano, M.A. 2007. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany* **58**: 147–159.

Fereres, E., Goldhamer, D. and Sadras, V. 2012. Yield response to water of fruit trees and vines: guidelines. In: *Crop Yield Response to Water*. *FAO Irrigation and Drainage Paper* **66**: 246–296.

Gangwar, K.S., Singh, K.K., Sharma, S.K. and Tomar, O.K. 2006. Alternative tillage and crop residue management in wheat after rice in sandy loam soils of Indo-Gangetic plains. *Soil and Tillage Research* **88**: 242–252.

Gharaibeh, M.A., Rusan, M.J., Eltaif, N.I. and Shunnar, O.F. 2014. Reclamation of highly calcareous saline-sodic soil using low quality water and phosphogypsum. *Applied Water Science* **4**: 223–230.

Giampietro, M. 1994. Sustainability and technological development in agriculture. *Bio Science* **44**: 677–689.

Goldman, A. and Smith, J. 1995. Agricultural transformations in India and Northern Nigeria: exploring the nature of green revolutions. *World Development* **23**: 243–263.

Gopalakrishnan, M. and Kulkarni, S. A. 2007. Agricultural land drainage in India. *Irrigation and Drainage* **56**: 59–67.

Gregory, P.J., Ingram, J.S.I., Andersson, R., Betts, R.A., Brovkin, V., Chase, T.N., Grace, P.R., Gray, A.J., Hamilton, N., Hardy, T.B., Howden, S.M., Jenkins, A., Meybeck, M., Olsson, M., Ortiz–Monasterio, I., Palm, C.A., Payn, T.W., Rummukainen, M., Schulze, R.E., Thiem, M., Valentin, C. and Wilkinsona, M.J. 2002. Environmental consequences of alternative practices for intensifying crop production. *Agriculture, Ecosystems and Environment* **88**: 279–290.

Gupta, R.K., Naresh, R.K., Hobbs, P.R., Jiaguo, Z. and Ladha, J.K. 2003. Sustainability of post-green revolution agriculture: the rice–wheat cropping systems of the Indo-Gangetic Plains and China. (In) *Improving the productivity and sustainability of Rice–Wheat Systems: Issues and Impacts,* pp. 1–25.

Gupta, R K. And Abrol, I.P. 2000. Salinity build-up and changes in the rice–wheat system of the Indo-Gangetic Plains. *Experimental Agriculture* **36**: 273–284.

Gupta, R. and Seth, A. 2007. A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic plains (IGP). *Crop Protection* **26**: 436–447.

Gupta, S.K. 2002. A century of subsurface drainage research in India. *Irrigation and Drainage Systems* **16**: 69–84.

Gupta, S.K. 2015. Reclamation and management of water-logged saline soils. *Agricultural Research Journal* **52**: 104–115.

Hazell, P.B.R. 2009. The Asian Green Revolution. IFPRI Discussion Paper 00911. International Food Policy Research Institute, Washington DC, USA.

Hira, G.S. and Singh, N.T. 1980. Irrigation water requirement for dissolution of gypsum in sodic soil. *Soil Science Society of America Journal* **44**: 930–933.

Hulugalle, N.R. McCorkell, B. E., Weaver, T. B. and Finlay, L.A. 2010. Managing sodicity and exchangeable K in a dryland Vertisol in Australia with deep tillage, cattle manure, and gypsum. *Arid Land Research and Management* **24**: 181–195.

ICAR–CSSRI. 2015. *ICAR–Central Soil Salinity Research Institute Vision 2050*. Indian Council of Agricultural Research, New Delhi.

Janmaat, J. 2004. Calculating the cost of irrigation induced soil salinization in the Tungabhadra project. *Agricultural Economics* **31**: 81–96.

Jha, S. Srinivasan, P.V. and Landes, M.R. 2007. Indian wheat and rice sector policies and the implications of reform. *USDA–ERS Economic Research Report* **41**, p. 43.

Lambers, H. 2003. Introduction, dryland salinity: a key environmental issue in southern Australia. *Plant and Soil* **257**: 5–7.

Lebron, I., Suarez, D.L. And Yoshida, T. 2002. Gypsum effect on the aggregate size and geometry of three sodic soils under reclamation. *Soil Science Society of America Journal* **66**: 92–98.

Lynch, J.P. 2007. Roots of the second green revolution. *Australian Journal of Botany* **55:** 493–512.

Mandal, S., Sarangi, S.K., Burman, D., Bandyopadhyay, B.K., Maji, B., Mandal, U.K. and Sharma, D.K. 2013. Land shaping models for enhancing agricultural productivity in salt affected coastal areas of West Bengal–an economic analysis. *Indian Journal of Agricultural Economics* **68** : 389–401.

Manjunatha, M.V., Oosterbaan, R.J., Gupta, S.K., Rajkumar, H. and Jansen, H. 2004. Performance of subsurface drains for reclaiming waterlogged saline lands under rolling topography in Tungabhadra irrigation project in India. *Agricultural Water Management* **69**: 69–82.

Matson, P.A., Parton, W.J., Power, A.G. and Swift, M. J. 1997. Agricultural intensification and ecosystem properties. *Science* **277**: 504–509.

Minhas, P.S. 1996. Saline water management for irrigation in India. *Agricultural Water Management* **30**: 1–24.

Mmolawa, K. and Or, D. 2000. Root zone solute dynamics under drip irrigation: A review. *Plant and Soil* **222**: 163–190.

Mounzer, O., Pedrero-Salcedo, F., Nortes, P.A., Bayona, J.M., Nicolás-Nicolás, E. and Alarcón, J. J. 2013. Transient soil salinity under the combined effect of reclaimed water and regulated deficit drip irrigation of Mandarin trees. *Agricultural Water Management* **120**: 23–29.

Munns, R. 2005. Genes and salt tolerance: bringing them together. *New Phytologist* **167**: 645–663.

Murty, M.N. and Kumar, S. 2011. Water pollution in India an economic appraisal. *India Infrastructure Report* **19**: 285–298.

Naresh, R.K., Minhas, P.S., Goyal, A. K., Chauhan, C.P.S. and Gupta, R. 1993. Conjunctive use of saline and non-saline waters. II. Field comparisions of cyclic uses and mixing for wheat. *Agricultural Water Management* **23**: 139–148.

Niazi, T. 2004. Rural poverty and the green revolution: the lessons from Pakistan. *Journal of Peasant Studies* **31**: 242–260.

Oron, G., DeMalach, Y., Gillerman, L., David, I. and Rao, V. P. 1999. Improved saline-water use under subsurface drip irrigation. *Agricultural Water Management* **39**: 19–33.

Oster, J.D. 1994. Irrigation with poor quality water. *Agricultural Water Management* **25**: 271–297.

Oster, J.D. and Frenkel, H. 1980. The chemistry of the reclamation of sodic soils with gypsum and lime. *Soil Science Society of America Journal* **44**: 41–45.

Pimental, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E. and Nandagopal, S. 2004. Water resources: agricultural and environmental issues. *BioScience* **64** : 909–918.

Pimentel, D. Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Christ, S., Shpritz, L., Fitton, L., Saffouri, R. and Blair, R. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science–AAAS–Weekly Paper Edition* **267**: 1,117–1,122.

Pingali, P.L. 2012. Green Revolution: Impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences **109** : 12,302–12,308.

Pingali, P.L. and Rosegrant, M.W. 1994. *Confronting the environmental consequences of the Green Revolution in Asia*. EPTD Discussion Paper No. 2, International Food Policy Research Institute (IFPRI), Washington DC, USA.

Pinstrup–Andersen, P. and Hazell, P.R.B. 1985. The impact of the Green Revolution and prospects for the future. *Food Reviews International* **1**: 1–25.

Pinstrup–Andersen, P. and Pandya-Lorch, R. 1998. Food security and sustainable use of natural resources: a 2020 vision. *Ecological Economics* **26**: 1–10.

Qadir, M. and Oster, J.D. 2004. Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. *Science of the Total Environment* **323**: 1–19.

Qadir, M., Qureshi, R.H. and Ahmad, N. 1996. Reclamation of a saline-sodic soil by gypsum and *Leptochloa fusca*. *Geoderma* **74**: 207–217.

Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R. J., Drechsel, P. and Noble, A. D. 2014. Economics of saltinduced land degradation and restoration. *Natural Resources Forum* **38**: 282–295.

Ram, J., Garg, V. K., Toky, O.P., Minhas, P.S., Tomar, O.S., Dagar, J.C. and Kamra, S.K. 2007. Biodrainage potential of *Eucalyptus tereticornis* for reclamation of shallow water table areas in north-west India. *Agroforestry Systems* **69**: 147–165.

Raney, T. 2007. Sowing a gene revolution. *Scientific American* **297**: 104–111.

Ritzema, H.P., Satyanarayana, T.V., Raman, S. and Boonstra, J. 2008. Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. *Agricultural Water Management* **95**: 179–189.

Rozema, J. and Flowers, T. 2008. Crops for a salinized world. *Science* **322**: 1,478–1,480.

Sepaskhah, A.R. and Ahmadi, S.H. 2010. A review on partial rootzone drying irrigation. *International Journal of Plant Production* **4**: 241–258.

Shabala, S. 2013. Learning from halophytes: physiological basis and strategies to improve abiotic stress tolerance in crops. *Annals of Botany*. doi:10.1093/aob/mct205.

Shah, T. 2011. Past, present, and the future of canal irrigation in India. *India Infrastructure Report,* pp. 70–87.

Shahare, P.U., Ghougule, B.A. and Ubale, S.S. 2002. Soil salinity and reclamation efforts in pre–independent India. *Asian Agri-History* (India) **6**: 243–260.

Sharma, D.K. and Singh, A. 2015. Salinity research in India: achievements, challenges and future prospects. *Water and Energy International* **58**: 35–45.

Sharma, D.K. and Singh, A. 2016. Greening the degraded lands: achievements and future perspectives in salinity management in agriculture. (In) *Natural Resource Management in Arid and Semi–Arid Ecosystem for Climate Resilient Agriculture*, pp. 1–14, Pareek, N.K. and Arora, Sanjay (Eds), Soil Conservation Society of India, New Delhi.

Sharma, D.P., Rao, K.V.G.K., Singh, K.N., Kumbhare, P.S. and Oosterbaan, R. J. 1994. Conjunctive use of saline and non-saline irrigation waters in semi-arid regions. *Irrigation Science* **15**: 25–33.

Sharma, P.C., Kaledhonkar, M.J., Thimappa, K. and Chaudhari, S.K. 2016a. Reclamation of waterlogged saline soils through subsurface drainage technology. ICAR–CSSRI/Karnal/ Technology Folder/ 2016/02, p. 4.

Sharma, P.C., Thimappa, K., Kaledhonkar, M.J. and Chaudhari, S.K. 2016b. Reclamation of alkali soils through gypsum technology. ICAR–CSSRI/Karnal/Technology Folder/2016/01, p.4.

Shukla, A.K. and Misra, P.N. 1993. Improvement of sodic soil under tree cover. *Indian Forester* **119**: 43–52.

Singh, A., Nath Panda, S., Flugel, W.A. and Krause, P. 2012. Waterlogging and farmland salinisation: causes and remedial measures in an irrigated semiarid region of India. *Irrigation and Drainage* **61**: 357–365.

Singh, G., Babu, R., Narain, P., Bhushan, L.S. And Abrol, I.P. 1992. Soil erosion rates in India. *Journal of Soil and Water Conservation* **47**: 97–99.

Singh, R.B. 2000. Environmental consequences of agricultural development: a case study from the Green Revolution state of Haryana, India. *Agriculture, Ecosystems and Environment* **82**: 97–103.

Singh, J. and Singh, J.P. 1995. Land degradation and economic sustainable. *Ecological Economics* **15** : 77–86.

Singh, S.K., Verma, C.L. and Sharma, D.K. 2014. Plant height model for *Eucalyptus* plantations for biodrainage use. *International Journal of Research in Engineering and Technology* **3**: 250–259.

Singh, S.K., Singh, R., Kumar, S., Narjary, B., Kamra, S.K. and Sharma, D.K. 2014. Productive utilization of sodic water for aquaculture-led integrated farming system: a case study. *Journal of Soil Salinity and Water Quality* **6**: 28–35.

Smith, J., Barau, A.D., Goldman, A. and Mareck, J.H. 1994. The role of technology in agricultural intensification: The evolution of maize production in the Northern Guinea Savanna of Nigeria. *Economic Development and Cultural Change* **42**: 537–554.

Stoate, C., Boatman, N.D., Borralho, R.J., Carvalho, C.R., De Snoo, G.R. and Eden, P. 2001. Ecological impacts of arable intensification in Europe. *Journal of Environmental Management* **63**: 337–365.

Stoll, M. Loveys, B. And Dry, P. 2000. Hormonal changes induced by partial rootzone drying of irrigated grapevine. *Journal of Experimental Botany* **51**: 1,627–1,634.

Swaminathan, M.S. 2006. An evergreen revolution. *Crop Science* **46**: 2,293–2,303.

Swaminathan, M.S. 1968. The age of algeny, genetic destruction of yield barriers and agricultural transformation. Presidential Address, Agricultural Science Section, 55th Indian Science Congress, January 1968. *Proceedings of the Indian Science Congress*, Varanasi, Uttar Pradesh, India.

Tilman, D., Balzer, C., Hill, J. and Befort, B.L. 2011. Global food demand and the sustainable intensification of agriculture.

Proceedings of the National Academy of Sciences **108**: 20260–20264.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R. and Polasky, S. 2002. Agricultural sustainability and intensive production practices. *Nature* **418**: 671–677.

UNEP. 2002. Vital water graphics: an overview of the state of the world's fresh and marine waters. *http://www.unep.org/vitalwater***.**

Valipour, M. 2014. Drainage, waterlogging, and salinity. *Archives of Agronomy and Soil Science* **60**: 1,625–1,640.

Varshney, A. 1989. Ideas, interest and institutions in policy change: Transformation of India's agricultural strategy in the mid-1960s. *Policy Sciences* **22**: 289–323.

Vitousek, P.M., Mooney, H.A., Lubchenco, J. and Melillo, J.M. 1997. Human domination of Earth's ecosystems. *Science* **277**: 494–499.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Reidy Liermann, C. and Davies, P. M. 2010. Global threats to human water security and river biodiversity. *Nature* **467**: 555–561.

Welch, R.M. 2002. The impact of mineral nutrients in food crops on global human health. In: *Progress in Plant Nutrition: Plenary Lectures of the XIV International Plant Nutrition Colloquium,* pp. 83–90. Springer, Netherlands.

Welch, R.M. and Graham, R.D. 1999. A new paradigm for world agriculture: meeting human needs Productive, sustainable, nutritious. *Field Crops Research* **60**: 1–10.

Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M. and Wade, A.J. 2009. A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal* **54**: 101–123.

Wichelns, D. and Qadir, M. 2015. Achieving sustainable irrigation requires effective management of salts, soil salinity, and shallow groundwater. *Agricultural Water Management* **157**: 31–38.

Yeo, A. 1998. Predicting the interaction between the effects of salinity and climate change on crop plants. *Scientia Horticulturae* **78**: 159–174.