Perspectives for Bio-management of Salt-affected and Waterlogged Soils in Pakistan

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Abstract

Waterlogging and salinity have afflicted about 4.5 million ha of irrigated lands in Pakistan which has reduced production potential of the Indus Basin by 25 %. Over the last 40 years, Pakistan has adopted engineering, reclamation, and biological measures to rehabilitate these soils. Engineering solutions involved implementation of large-scale Salinity Control and Reclamation Projects (SCARPs) covering 8 million ha of land with an estimated cost of US$ 2 billion. Reclamation of saline soils was mainly achieved by leaching excess salts and the use of chemicals such as gypsum and acids. Despite initial success, the success of these initiatives has been limited due to several factors. Operational and maintenance cost of drainage projects proved a financial burden for the government and was discontinued. Nonavailability of subsidized gypsum and chemicals restricted the capacity of farmers to reclaim saline soils. As an alternative to engineering and reclamation solutions, Pakistan has made considerable progress in bioremediation by identifying and establishing plant species that can effectively lower groundwater tables and reclaims saline soils. The bioremediation systems also help in sequestering carbon, diminishing the effects of wind erosion, providing shade and shelter, and in enhancing the biodiversity. In order to derive the benefits of such efforts, bioremediation plantations have to be extended over relatively large areas. Therefore, it may not be an attractive proposition to individual farmers unless there are cooperative efforts. Involving the farming communities in such bioremediation programs seems promising for their economic and social well-being in countries such as Pakistan where individual land holdings are small.

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Introduction

Globally approximately one billion hectares of lands are salt-affected (Wicke et al. 2011). Despite large-scale contribution in securing food and fiber needs of the increasing population, irrigated agriculture is usually blamed for negative environmental impacts such as soil salinization. The salt-affected soils occupy more than 20 % of irrigated lands (Ghassemi et al. 1995), and this process continues to occur at an estimated rate of 0.25–0.50 million hectares each year (FAO 2000). The large extent of salt-affected soils is of special concern because they greatly reduce agricultural productivity. In South Asia, the continuous expansion of salt-affected soils is of even greater concern due to increasing demand for food for the fast-growing population. In Pakistan, salinity has affected about 4.5 Mha (Qureshi 2011). Poor irrigation management practices, lack of appropriate drainage systems, and the use of poor-quality irrigation water are the major reasons for waterlogging and salinity problems in India and Pakistan. In Bangladesh, seawater intrusion has caused soil salinity problems for about 1 Mha of coastal zone of the Ganges–Brahmaputra River Delta (Hossain 2010). This situation has threatened the food security of these countries and warrant immediate attention for inexpensive and environmentally acceptable solutions for reclaiming and managing these soils (Qadir and Oster 2002).

For ensuring future food security in arid and semiarid regions, the use of salt-affected soils and marginal-quality waters can play a key role to improve crop production and mitigate environmental effects. This, however, will require a comprehensive approach to soil, water, and crop management which necessarily should include rehabilitation of degraded lands, reclamation of new lands, and adoption of improved irrigation practices for increasing land and water productivity and decreasing environmental problems. In irrigated areas, irrigation management needs to be improved to reduce volumes of drainage water to avoid disposal and associated environmental problems (Wichelns 2009). As the increasing competition for freshwater resources has already reduced allocations of freshwater for agriculture in many regions (Tilman et al. 2002), the reuse of saline and sodic drainage water generated by irrigated agriculture and marginal-quality water generated by municipalities need to be explored (Rhoades 1999; Oster 2000; Qadir and Oster 2004).

Conventional agriculture is usually not considered economically viable on salt-affected soils due to low crop yields and low economic returns (Qadir and Oster 2004). Furthermore, physical remediation of salt-affected soils is complex, expensive, and time-consuming for many farmers due to lack of proper guidance and training. Therefore, for these soils, forestry and agroforestry systems could be an attractive alternative, because many tree species are tolerant to soil salinity and their cultivation can help in regeneration of these soils (Wicke et al. 2013). Agroforestrysystems have proved economically viable land use options in many areas of South Asia and the world (Kaur et al. 2002; Masters et al. 2007).

In Pakistan, about half of the 4.5 Mha of salt-affected lands are located in irrigated areas (Qureshi et al. 2008). It is estimated that salt-affected lands have reduced the production potential of irrigated lands by almost 50 % (Qureshi et al. 2008). Over the past four decades, numerous efforts have been made to reclaim and manage salt-affected and waterlogged soils through engineering, reclamation, and biological measures. However, the success has been limited due to several reasons. High operational and maintenance costs make drainage projects an economic burden for the governments, whereas nonavailability of subsidized gypsum and other amendments restricted farmers to reclaim their lands. As an alternative, bioremediation measures were adopted by farmers. This chapter discusses the causes and extent of soil salinity and waterlogging in Pakistan and reviews the impact of different interventions made for the management of salt-affected and waterlogged soils with special emphasis on bioremediation measures. Lessons learned and steps needed for future management of these troubled soils are also presented.

Extent of Salt-affected Waterlogged Soils in Pakistan

Out of the total geographical area of 79.61 Mha of Pakistan, more than 21 Mha is cultivated. About 59 % of the agricultural area is located in the Punjab province, which produce more than 90 % of the total grain production of the country. Next is the Sindh province with about 23 % of the total agricultural lands. Rest 18 % of the area is almost equally shared by Khyber Pakhtunkhwa (KP) and the Balochistan provinces. In arid and semiarid regions, drainage is considered as a complimentary activity with the irrigation to avoid groundwater table rise and consequent soil salinization. However, despite considerable progress in irrigation development, provision of drainage facilities was never given a priority in Pakistan. This negligence causes groundwater tables to rise in most of the canal command areas due to persistent seepage over the years from unlined earthen canals and from a large network of distributing channels and percolation losses from irrigated fields. As a result, the groundwater table rose rapidly in vast irrigated areas to within 1.5 m of the soil surface.

The groundwater table in the canal command areas of Pakistan exhibits an annual cycle of rise and fall. In most of the Indus plain, the groundwater table is at its lowest level prior to the monsoon (April/June) season, and as a result of the *kharif* (summer) canal supplies and the effects of the monsoon rains, it rises and comes close to the land surface in October, after which it begins to decline again. Based on their annual monitoring of groundwater levels all over Pakistan, Water and Power Development Authority (WAPDA) of Pakistan has estimated that for 4.7 million ha (30 % of the irrigated area), the groundwater table is within 1.5 m of the soil surface after the monsoon season. Prior to the monsoon season, this area is reduced to about 2 Mha or 13 % of the irrigated area (Fig. 1). The Punjab province has about 25 % of its irrigated area severely waterlogged, while in Sindh, this figure is about 60 %. Due to the presence of this shallow, saline groundwater, about 40,000 ha are annually abandoned within the Indus basin due to secondary salinization (WAPDA 2007).

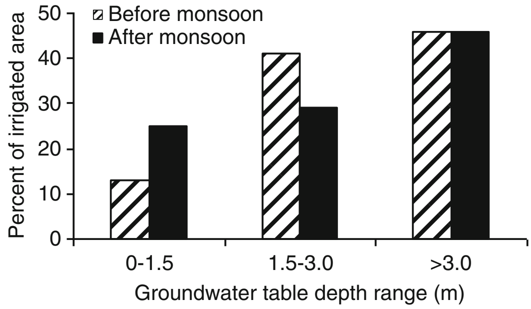

Fig. 1 Percentage of area under different water table depths before and after monsoon

The salt-affected soils associated with the use of poor-quality groundwater for irrigation have become an important ecological entity of the Indus basin. Latest soil salinity survey conducted by WAPDA shows that the extent of salt-affected lands has decreased to about 4.5 Mha from about 6 Mha in the 1980s (WAPDA 2007). The reduction in salinity (surface and profile) is primarily due to increased irrigation water supply from surface and groundwater sources, better water management, increased cropping intensity, and measures taken to reclaim the waterlogged and salt-affected lands. Surface salinity trends in four provinces of Pakistan are shown in Fig. 2 (WAPDA 2007). It is clear that still salinity problems in the Sindh are much more severe than in other provinces.

About 21 % of lands in Pakistan are saline, out of which about 7 % (1.5 Mha) is strongly saline. The problems of soil salinity are more serious in Sindh province (lower part of the Indus basin), where about 50 % of the area is saline (Qureshi 2011). This is mainly because of the presence of marine salts, poor natural drainage conditions, and the use of poor-quality groundwater for irrigation because surface water supplies in the Sindh province are far less than the actual crop water requirements. Furthermore, leaching opportunities are also very limited due to highly saline soils at shallow depths and highly saline groundwater at deeper depths (Bhutta and Smedema 2007). These problems have brought into question the sustainability of the system and the capacity of Pakistan to feed its growing population in the coming decade unless better management institutions are introduced.

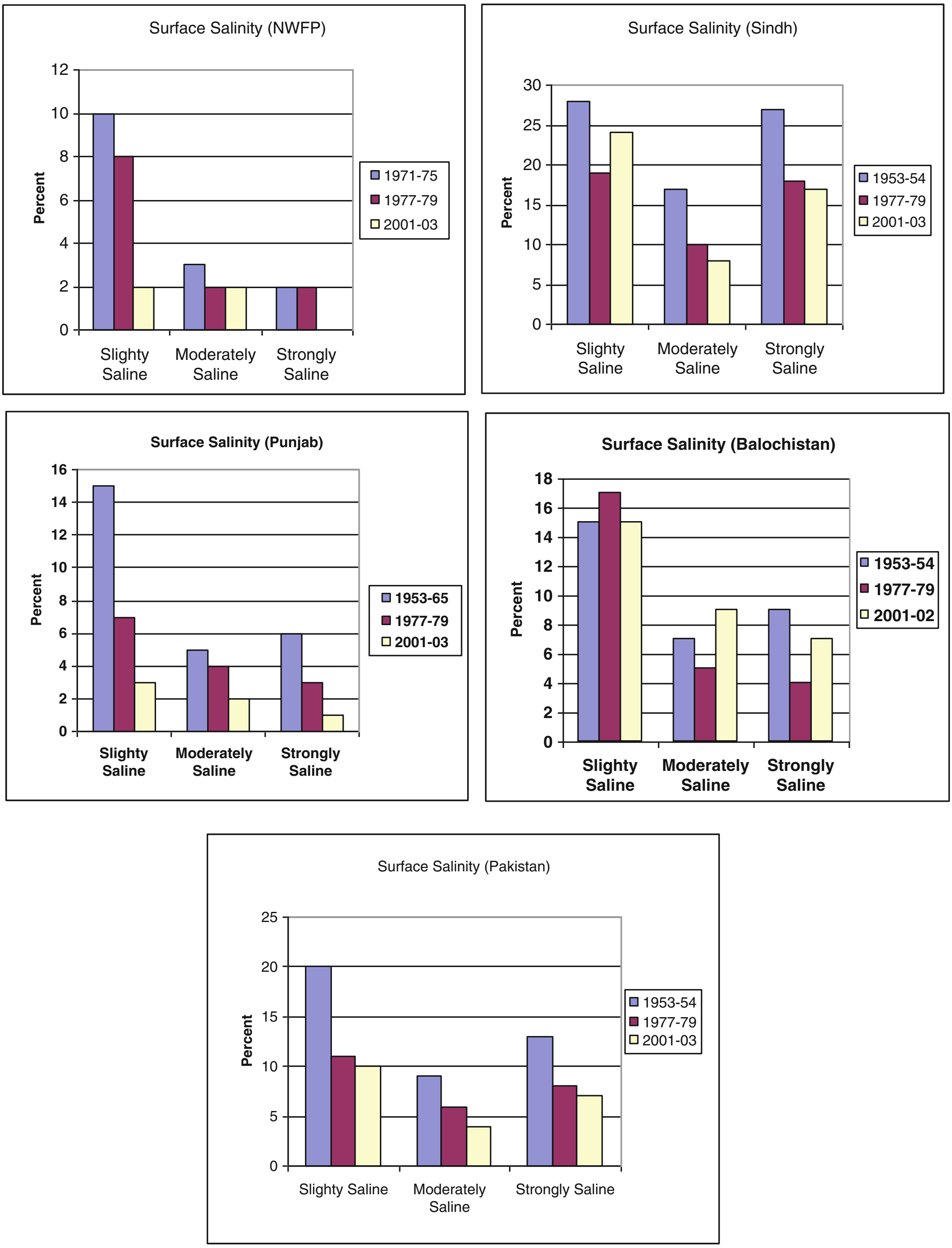

Fig. 2 Country- and province-wise distribution of salt-affected area (WAPDA 2007)

Table 1 Classification of salt-affected soils in Pakistan

Classification of salt-affected soils	Area affected (million ha)	Characteristics
Slightly saline sodic	0.6	Slight salinity-sodicity problem, occurring as patches (about 20 % of the area) in cultivated fields
Porous saline sodic	1.4	Saline sodic throughout the root zone, porous, and pervious to water
Severely saline sodic	0.8	Have high groundwater tables, dense, and nearly impervious to water
Soils with sodic tube well water	1.7	Severely sodic due to application of sodic tube well water, contain high concentrations of carbonates and bicarbonates, and almost impervious

Modified from Qureshi and Barrett-Lennard (1998)

The problems of soils in the Indus basin are not only of salinity but also of sodicity. About 70 % of the tube wells in the Indus basin pump sodic water, which contain high concentrations of carbonate and bicarbonate. Application of this quality of water for irrigation turns the soils to saline sodic affecting soil structure and infiltration rates, thereby restricting the growth of conventional crops. Salt-affected soils of the Indus basin are usually classified into four types. The area affected and the characteristics of these four soil types are given in Table 1.

The above facts indicate that the agricultural sector suffers deeply from both waterlogging and salinity. About 75 % of the population and about half of the gross national product (GNP) are directly or indirectly related to the agricultural sector. This shows that the problems of waterlogging and salinity are not just agricultural problems but that they do affect the country as a whole and ultimately the social fabric of Pakistani society. Waterlogging and salinity have very adverse social and economical effects on communities in Pakistan, causing poor living standards in affected areas and health problems for humans and animals. This situation has forced the local population to migrate to other areas.

Strategies Adopted in Pakistan

In Pakistan, engineering, reclamation, and bioremediation strategies have been used for the rehabilitation of salt-affected and waterlogged soils. Engineering approaches include installation of surface drainage, subsurface drainage, and vertical drainage systems to drain excess water from soils. Surface drainage systems were not only used to remove excess water from agricultural fields and also as conveyance channels for urban and industrial waste water and subsurface drainage systems. Due to mixing of industrial water with the agricultural drainage water, the quality of water in surface drains was deteriorated which restricted its reuse for agricultural purposes and increased the volume of disposal effluent. Reclamation of salt-affected soils was mainly done through leaching of salts by applying higher levels of irrigation, the use of gypsum or acids, physical removal of salts, and growing salt-tolerant plants. Bioremediation approaches involve using salt-tolerant crops on highly salt-affected soils with saline water. These approaches are discussed below in the context of Pakistan.

Engineering Strategies

After detailed survey of groundwater table depth and salinity in the 1950s, Pakistan decided to install 14,000 tube wells in fresh groundwater areas (covering 2.6 Mha of irrigated land) for lowering groundwater table to control waterlogging and to increase irrigation supplies at the farm gate by mixing pumped groundwater with the canal water. Under this Salinity Control and Reclamation Projects (SCARPs), 63 projects were completed during the last four decades to cover about 8 Mha with an estimated cost of US$ 2 billion (Qureshi 2011). The SCARPs project were successful in controlling or even reversing the waterlogging and salinity problems and providing additional water for irrigation. As a result, cropping intensities increased from 84 to 115 % in most SCARP areas. However, over time, increased operational and maintenance costs and increasing salinity of the pumped groundwater reduced the efficiency of SCARPs which resulted in rising water tables and lower crop yields.

In the mid-1970s, thinking shifted toward horizontal (pipe) drainage systems with the perception that over time drainage water quality will be improved which will increase the possibility of using drainage water for irrigation. Furthermore, the disposal problems will be reduced. Since then, about ten major horizontal drainage projects (12,600 km of pipe drains) have been completed in different parts of Pakistan (Qureshi et al. 2008). The major bottleneck in the successful operation of these drainage systems was the safe disposal of saline drainage effluent. To overcome this issue, Pakistan constructed a 2000-km long surface drain on the left side of the Indus River to transport drainage water of more than 500,000 ha of land to the sea (Qureshi et al. 2008). Initial results of this drain were very encouraging, but soon surrounding areas of this unlined drain started becoming waterlogged due to seepage. This escalated interprovincial dispute between Punjab and Sindh provinces, which resulted in impasse of drainage water from Punjab passing through Sindh province and finally into sea. This exacerbates waterlogging problems in Punjab.

Reclamation Strategies

The presence of excessive salts in the soil does not have adverse impacts on soil structure and its physical and hydraulic properties. In many cases, saline conditions may have favorable effects on soil structure (Quirk 2001). The soil structural problems mainly stems from the presence of sodium in the soil. Sodic soils exhibit structural problems created by physical process (slaking, swelling, and dispersion of clay) and specific conditions (surface crusting and hard setting) (Sumner 1993; Wicke et al. 2011). These soils can be reclaimed by providing a source of calcium (Ca^{2+}) to replace excessive sodium Na^{+} from the cation exchange sites (Qadir and Oster 2004). The replaced sodium is leached from the root zone through excessive irrigation.

In Pakistan, different strategies were applied for reclaiming sodic soils. Agricultural and industrial waste, e.g., farmyard manure and by-products of the sugar industry, have been used to improve sodic soils. A large range of chemicals (sulfur, sulfuric acid, and aluminum sulfate) have also been tested to provide calcium source to sodic soils. Gypsum was widely used as an amendment for sodic soils because it was highly subsidized by the government (US$ 0.25 per 50 kg bag) (Qureshi and Barrett-Lennard 1998). However, over time, the cost of these amendments has increased due to decrease in government subsidies to farmers. In addition, low quality of amendments and difficulties in their timely availability have discouraged reclamation through chemical means especially for the subsistence farmers. At the government level, there is no nationwide action program for promoting reclamation efforts. Efforts by local governments are mainly confined to supporting field-level research and providing subsidies to the farmers for the use of gypsum. Farmers in Pakistan have also used physical methods of surface scraping and deep plowing in a desperate attempt to reclaim their saline-(sodic) soils.

Planting of salt-tolerant crops has also been experimented as a reclamation intervention. Some crops are more salt tolerant at certain stages of development than others, e.g., sugar beet at germination, barley at the early seedling stage, and rice at the flowering stage. Although extremely salt sensitive, rice paddy has been found to be a better crop than others for reclamation of saline-sodic soils, as it provides sufficient water for leaching. Similarly, barley and cotton can withstand higher levels of salinity under good drainage conditions.

Bioremediation/Agroforestry Strategies

The limited success in controlling waterlogging and salinity problems despite huge investments prompted scientists and engineers to think about other options which are less expensive, more sustainable, and cost-effective. One of the promising solutions is lowering water table through biological means. The use of bioremediation in waterlogged areas is based on the concept of enhanced evapotranspiration (Jeet-Ram et al. 2011). The biological approach emphasizes the use of highly saline water and lands on a sustained basis through profitable and integrated use of the genetic resources embedded in plants, animals, fish, and insects and improved agricultural practices. This approach attempts to promote bio-reclamation techniques using salt-tolerant plants, bushes, trees, and fodder grasses. Plants, particularly trees, are commonly referred to as biological pumps and play an important role in the overall hydrological cycle in a given area. Bioremediation systems are considered beneficial compared to conventional subsurface drainage systems because in bioremediation systems we do not need to

- Induce water flow through the soil toward a tube well or pipe drain
- Install collector and main drains to transport water out of the draining area
- Operate pumps for evacuating drained water and then transport to disposal sites
- Create disposal sites (e.g., by evaporation ponds)

The long-term sustainability of bioremediation has been intensely debated. Smedema (1997, 2000) has suggested that bioremediation could be considered for waterlogged landscape depressions and canal seepage interception and could be applied in "parallel field drainage" arrangements as an alternative to conventional field drainage systems. In Australia, it is now widely accepted that enhanced evapotranspiration bioremediation sites will eventually succumb to salinity, unless conventional drainage systems are installed to control salt balance by removal of saline drainage effluent (Heuperman 2000).

Studies done in Pakistan (Qureshi and Barrett-Lennard 1998; Ghafoor et al. 2004; Shah et al. 2011) have shown that highly saline waters could be used to grow salt-tolerant fodder grasses to improve the quality and quantity of livestock. Management practices of these waters include the use of chemical amendments, organic matter, and mineral fertilizers and judicious selection of salt-tolerant forages and grasses. Trees and plants act as biological drainage agents, helping to lower water table depths—a very simple as well as energy-saving method. This is basically a "pro-poor" approach that enhances the income of poor farmers who otherwise might leave their lands barren.

Bioremediation approaches experimented in Pakistan mainly used salt-tolerant crops to get maximum benefit from saline land and water. Soils that are saline down to 0.45-m soil depth have been successfully reclaimed by growing *kallar* grass (*Leptochloa fusca*) over a period of 5 years, after which the field can be put to normal cropping. The growth of perennial forage grasses is also important in salt-affected areas. Rhoades grass (*Chloris gayana*), Tall wheatgrass (*Elytrigia elongata*), and many other species have been shown to have tolerance to salt stress. Saltbushes such as river saltbush (*Atriplex amnicola*) are highly salt-tolerant forage bushes (Qureshi and Akhtar 2002). *Kallar* grass is most commonly used as a forage plant. It does not retain most of the taken up salts; hence, it remains reasonably palatable for farm animals. As a result, large tracts of *kallar* grass are being used as a sole source of fodder for livestock (Shah et al. 2011). So far, no adverse effects of feeding *kallar* grass to animals have been reported. Therefore, its production can be further encouraged in salt-affected areas.

In Pakistan, bioremediation has also been used for the reclamation of waterlogged soils. Bioremediation involves growing certain categories of plants that habitually draw their main water demand directly from the groundwater. A number of trees are in this group, including poplar (*Populus deltoides*), *Eucalyptus*, *Tamarix*, mesquite (*Prosopis juliflora*), and *Acacia nilotica*. Similarly, nonwoody plants such as bushes, sedges, grasses, and herbs can develop deep-rooted systems that contact groundwater (Choudhry and Bhutta 2000). Any significant effect of such plantation on the water table would be expected only when the plants occupy a large enough portion of the catchments so that their total water use approaches the total recharge for the catchments. In Pakistan, the capacity of productive tree plantations to extract shallow groundwater is seen as a valuable tool for controlling rising water tables and salinity.

Bioremediation Species Used in Pakistan

Selection of plant species for bioremediation depends on the environmental conditions for which they are planned. Salt tolerance will be an important criterion for (potentially) saline discharge environments, and water use considerations will prevail in recharge control situations where salinity is of no concern and in channel seepage scenarios with low-salinity water supply. For agricultural crops, salt- tolerance information based on Maas and Hoffman (1977) is most commonly used. For nonagricultural tree and bush species, reliable information is more difficult to obtain. Marcar et al. (1995) provided detailed information on the use of 30 tree species for use on salt-affected lands and less detailed summary descriptions for an additional 30 species. Schulz (1994) provided comparisons for five saltbush species grown on a range of saline irrigation regimes, whereas others investigated water use of different tree species under a range of saline conditions (Morris et al. 1998; Slavich et al. 1999; Cramer et al. 1999; Benyon et al. 1999).

For Pakistani conditions, Shah et al. (2000) provided information on crops, salt-tolerant trees, grasses, and saltbush. Khanzada et al. (1998) monitored the water use of *Acacia nilotica*, *A. ampliceps*, and *Prosopis pallida* on 3–5-year-old plantation sites with contrasting soil and groundwater salinity in the Indus Valley in Pakistan. Annual water use by *A. nilotica* was 1248 mm on a severely saline site and 2225 mm on a moderately saline site. This was considerably higher than the annual rainfall, indicating that much of the water was taken up from the saline water tables underlying the sites (20 dS m^{-1} at 1–1.5 m below surface at the saline site and 1.5 dS m^{-1} at 2 m below surface at the moderately saline site). It was concluded that trees can evaporate large volumes of saline groundwater; however, there may be accumulation of salts. Therefore, drainage system might be needed to evacuate the accumulated salts in the root zone to ensure long-term sustainability of this technology.

Fast-growing *Eucalyptus* species known for luxurious water consumption under excess soil moisture conditions are suitable for bioremediation (Shah et al. 2003). *Eucalyptus* species has a higher bioremediation potential as compared to relatively slow bio-drainers like *E. tereticornis* and *Pongamia pinnata* (Zhang et al. 2004). *E. tereticornis* and *Eucalyptus* hybrid are fast bio-drainers primarily due to their ability to display large leaf area (Angrish et al. 2009). Cloned *E. tereticornis* (Mysure gum) is fast growing, goes straight, and thus has low shading effect and has luxurious water consumption where excess soil moisture conditions exist. Because of fast growth rate, good wood properties, and carbon sequestration, world's *Eucalyptus* plantation area has increased to 19 million ha (Mha) (Iglesias and Wilstermann 2009).

In Pakistan, the use of *Eucalyptus* has significantly increased over the last three decades. A rough estimate that *Eucalyptus* plantings cover is about 10,000 ha. Of all *Eucalyptus* introduced in Pakistan to date, *E. camaldulensis* has proven most adaptable under all agroecological zones. Consequently, it has been planted more than other species; it is the prescribed species of all afforestation programs (Bilal et al. 2014). It is especially favored in arid and semiarid plains as single trees, in block and linear plantations, and is raised with or without artificial irrigation. The existing growing stock of *Eucalyptus* is mostly of *E. camaldulensis* and its numerous hybrid forms, occurring naturally. *Eucalyptus* is being grown in irrigated plantations of the government land and on farmlands of Punjab and Sindh. A recent survey shows that about 200 million trees have been planted in the Punjab on farmlands, mostly irrigated, of which *Eucalyptus* is 2.5 % (Shah et al. 2011).

During 1996–1998, the *E. camaldulensis* tree and saltbushes (*Atriplex amnicola* and *Atriplex lentiformis*) species have been successfully used to restore the productivity of about 400 hectare of salt-affected lands in the Faisalabad District of the Punjab province (Shah et al. 2011). This was followed by a UNDP- and AusAID-funded project, which was executed in three districts of the Punjab province. The unique feature of this project was the establishment of Salt Land User Groups (SLUGs) and Women's Interest Groups (WIGs) to encourage involvement of communities in the process of rehabilitation of marginal lands (Shah et al. 2011). During 2006–2010, bioremediation technology was further extended to 80,000 ha with a US$ 13 million financial assistance of the Asian Development Bank. Under this project, land rehabilitation of 45,000 ha was done by adopting an integrated approach, i.e., through gypsum application and tree plantation (Shah et al. 2011). In many other areas, farmers have adopted these species for reclaiming their lands.

Comparison of Bioremediation and Other Reclamation Strategies

Despite above advantages, bioremediation systems have certain shortcomings which can make their adoption restricted under certain circumstances. The efficiency of different plant species for the reclamation of saline-(sodic) soils is highly variable (Qadir and Oster 2004). In general, species with higher biomass production and tolerance against ambient salinity are more efficient in soil reclamation (Ghaly 2002; Kaur et al. 2002). The reduction in sodicity levels through bioremediation treatment was found to be 52 % compared to 62 % through chemical treatments (gypsum). Furthermore, bioremediation works well on coarse- to medium-textured, moderately saline, and saline-sodic soils.

Production systems based on salt-tolerant grasses and forage crops using saline irrigation water are considered more sustainable for bioremediation. If these systems are linked with a livestock production system, economic benefits can increase manifolds, and environmental problems of disposal of saline effluent can be minimized. Therefore, for the success of bioremediation systems, selection of plants capable of producing adequate biomass is very vital. The bioremediation technology is economically beneficially when there is a market for the bioremediation crops for forage and/or for firewood (Barrett-Lennard 2002). However, for the economic analysis of these technologies, one must also consider the value of rehabilitated lands in the long run.

In view of above, bioremediation can effectively contribute to lowering the groundwater table to reduce waterlogging and consequent salinity problems in irrigated and nonirrigated areas. Pakistani experience with bioremediation shows that involvement of communities in rehabilitation process through bioremediation can significantly contribute to rural development and the well-being of rural communities. The bioremediation systems are beneficial in producing timber, fruits, oils, and fuel wood, contributing to carbon sequestration, diminishing the effects of wind erosion, providing shade and shelter, functioning as windbreaks, yielding organic matter for fertilizer, enhancing biodiversity as flora and fauna flourishes, and diminishing air pollution (Heuperman et al. 2002).

One of the disadvantages of bioremediation is its requirement for large proportion of land area for its effectiveness, which might not be possible for an individual farmer to afford. Therefore, in countries like Pakistan where individual land holdings are very small, farmers have to make joint efforts for bioremediation. Bioremediation is also considered less effective in removing salts from the root zone and do not allow controlled drainage. Therefore, these systems need to be complimented with conventional drainage system for removing salts from the root zone. However, combining bioremediation with conventional drainage systems could yield potential results in reclaiming salt-affected and waterlogged soils.

Conclusions

The irrigated agriculture sector of Pakistan is encountering a great challenge in terms of waterlogging and salinity, which deprive farmers of productive resources and threaten their livelihoods. Pakistan has understood the significance of these issues, and efforts were started to overcome these problems through the implementation of waterlogging and salinity control projects. These projects mainly consisted of engineering work to install tube wells and surface and subsurface drains. Although engineering solutions help increase cropping intensities and yields, they fail to stop emergence of similar environmental problems in adjacent areas. For the reclamation of saline-sodic and sodic soils, the government promoted the use of gypsum and other physical methods such as acids and addition of organic matters. For this purpose, gypsum was subsidized by the government to facilitate farmers in the reclamation of troubled soils.

Considering the high installation and operational costs of engineering solutions, thinking of scientists diverted to more inexpensive and sustainable solutions such as biosaline agriculture. In the last 20 years, a wide range of research has been done on saline agriculture through the profitable and integrated use of genetic resources of plants, animals, fish, and insects and improved agricultural practices. For the success of saline agriculture in Pakistan, a number of salt-tolerant crop varieties and the use of improved planting techniques and fertilizers have been introduced. These technologies have shown very encouraging results in reclaiming saline and waterlogged soils. The growth of perennial forage grasses has been quite successful in Pakistan. Rhodes grass (*Chloris gayana*), Tall wheatgrass (*Elytrigia elongata*), and Puccinellia (*Puccinellia ciliata*) are the most popular examples. The incorporation of salt-tolerant trees and saltbushes into agricultural systems of salt-affected and waterlogged lands has the potential to increase crop and animal production and decrease land degradation. Such land improvements combined with improved agricultural practices will ensure that the current unsustainable trends in agriculture are reversed.

The success of saline agriculture necessitates more concerted efforts both at the public and private levels. The major areas of focus should be the enhancement of research capacity on different aspects of engineering, reclamation, and biological approaches. There is also a need to focus on action programs for the most seriously affected areas, capacity building of farmers, introduction of groundwater extraction regulations, and promotion of saline agriculture. Making these priorities in Pakistan is a basis for achieving sustainable irrigated agriculture and improved livelihoods.

The salt management issues in Pakistan are complex; therefore, an integrated approach dealing with irrigation and drainage issues is of paramount importance to sustain and improve the productivity of irrigated agriculture. For the future sustainability of irrigated agriculture, provision of drainage should be considered as a complimentary activity to irrigation because these two are interlinked through (1) over or inefficient irrigation as a cause of waterlogging and (2) the relationship between irrigation management and effluent disposal. Improved irrigation efficiencies and sustainable reuse of drainage water at the farm level can help in minimizing drainage effluent. Where relevant, farmers need to have access to the knowledge and inputs for reclaiming salt-affected lands through physical, chemical, and biological approaches. Timely availability of farm inputs such as good quality water, salt-tolerant germplasm, and promotion of saline agriculture through crop diversification options such as salt-tolerant medicinal and aromatic plant species can improve the capacity of individual farmers to be productive.

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