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Salt-induced land and water degradation in the Aral Sea basin: A challenge to sustainable agriculture in Central Asia

Manzoor Qadir, Andrew D. Noble, Asad S. Qureshi, Raj K. Gupta, Tulkun Yuldashev and Akmal Karimov

Abstract

Expansion of irrigated agriculture in the Aral Sea Basin in the second half of the twentieth century led to the conversion of vast tracks of virgin land into productive agricultural systems resulting in significant increases in employment opportunities and income generation. The positive effects of the development of irrigated agriculture were replete with serious environmental implications. Excessive use of irrigation water coupled with inadequate drainage systems has caused large-scale land degradation and water quality deterioration in downstream parts of the basin, which is fed by two main rivers, the Amu-Darya and Syr-Darya. Recent estimates suggest that more than 50% of irrigated soils are salt-affected and/or waterlogged in Central Asia. Considering the availability of natural and human resources in the Aral Sea Basin as well as the recent research addressing soil and water management, there is cause for cautious optimism. Research-based interventions that have shown significant promise in addressing this impasse include: (1) rehabilitation of abandoned salt-affected lands through halophytic plant species; (2) introduction of 35-day-old early maturing rice varieties to withstand ambient soil and irrigation water salinity; (3) productivity enhancement of high-magnesium soils and water resources through calcium-based soil amendments; (4) use of certain tree species as biological pumps to lower elevated groundwater levels in waterlogged areas; (5) optimal use of fertilizers, particularly those supplying nitrogen, to mitigate the adverse effects of soil and irrigation water salinity; (6) mulching of furrows under saline conditions to reduce evaporation and salinity buildup in the root zone; and (7) establishment of multipurpose tree and shrub species for biomass and renewable energy production. Because of water withdrawals for agriculture from two main transboundary rivers in the Aral Sea Basin, there would be a need for policy level interventions conducive for enhancing interstate cooperation to transform salt-affected soil and saline water resources from an environmental and productivity constraint into an economic asset.

Keywords: Soil salinity; Waterlogging; Salt-affected soils; Water quality; Magnesium-affected soils; Saline water; Central Asia.

1. Introduction

Central Asia is a geopolitical region extending from the Caspian Sea in the west, to China in the east, and from Russia in the north to Iran and Afghanistan in the south. The breakup of the Former Soviet Union in 1991 led to the emergence of five independent states in Central Asia, consisting of Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan. The region has a total area of 3,994,400 km² (FAO, 2008a) and a population of over 55 million. The climate in the region is classified as arid or semi-arid with mean annual precipitation varying between 600–800 mm in the mountainous zones to 80–150 mm in the desert regions that is predominantly distributed over the winter and spring.

Prior to independence from the Former Soviet Union, the economies of the Central Asian states were interdependent upon a centrally managed Soviet economy. Each state was agriculturally specialized according to specific agro-climatic zones, with production and marketing distributed through the entire Soviet trade system. Agriculture still
remains an important sector of the economy employing between 20 to 50% of the national labour force in different states (Paroda et al., 2004). Approximately 22 million people have direct or indirect reliance on irrigated agriculture for their livelihoods. The Gross Domestic Product (GDP) from agriculture ranges from 19% in Kazakhstan to 38% in the Kyrgyz Republic. This may well be an underestimation of the contribution of agriculture. The socio-economic development of Central Asia has historically been dependent on natural resources such as water and land. In the mid 1920s, the irrigated agriculture in the Syr-Darya River Basin covered approximately 991,000 ha. Irrigated agriculture and livestock production have dominated the economic development of these Central Asian countries over the past 30 years and by the 1960s, the area of irrigated land in the Aral Sea Basin had increased to 5.2 million ha. Further development of irrigated agriculture has led to the conversion of virgin lands into productive agricultural lands resulting in significant increases in employment opportunities and income generation. The extent of irrigated area within the territory of the Aral Sea Basin alone is 8.12 million ha (Dukhovny and Sokolov, 2005). With 9.61 million ha under irrigated agriculture, Central Asia is one of the largest irrigated regions in the world (FAO, 2008b). A map indicating five countries of Central Asia and the location of the Aral Sea is given for ready reference (Figure 1).

The positive effects of the development of irrigated agriculture over the decades have not been without negative environmental implications. Over-exploitation of water resources has caused widespread environmental degradation (Cai et al., 2003). For example, before large-scale irrigation, less than 8000 m$^3$ of water were used annually on a hectare of land. With the expansion of irrigated agriculture, the average annual water use has increased to 12,000–14,000 m$^3$ ha$^{-1}$ (Nazirov, 2005), indicating 50–75% increase in water use per unit area. Such excessive irrigation coupled with inadequate drainage has caused large-scale land degradation and water quality deterioration, particularly in downstream areas of the Aral Sea Basin. This is predominantly due to poor irrigation management and the lack of adoption of improved water...
saving irrigation techniques. Irrigation efficiencies of major irrigation schemes vary from 30 to 50% (Paroda et al., 2004; Nazirov, 2005).

Recent estimates reveal that more than 50% of irrigated soils in Central Asia are salt-affected and/or waterlogged (Dukhovny, 2005). Since the 1970s, the level of salts in river water has increased steadily as a result of discharge from drains associated with irrigated schemes back into the river systems. Analysis of the salt inflow and outflow shows that salts accumulate at an annual rate of 0.6 to 10 t ha\(^{-1}\) in the middle and lower reaches of the Amu-Darya Basin, and this is being exacerbated by years of below-average rainfall. In the lower reaches of the basin, the rate of salt accumulation is estimated to be 8 t ha\(^{-1}\) yr\(^{-1}\), even in wet years. In the Syr-Darya Basin, salts accumulate at a rate of 5.3 t ha\(^{-1}\) yr\(^{-1}\). These amounts are 5 to 10 times higher than in other river basins. The annual salt accumulation, for example, in the Indus Basin irrigation system is 1 t ha\(^{-1}\) (Qureshi et al., 2008). In addition to salt accumulation, about 30% of the irrigated land is affected by elevated levels of groundwater with implications for waterlogging. In the past, an extensive artificial drainage network covering 5.7 million ha was developed to address the problem. However, the actual coverage and effectiveness of the drainage network has been reduced to half the capacity in recent years due to a lack of investment in operation and maintenance.

The Aral Sea, which is fed by two main rivers, Amu-Darya and Syr-Darya, is situated in the centre of the Central Asian deserts and functions as a gigantic evaporator. The Sea, which was the fourth largest inland lake in the world before 1960, is now the largest inland salt reservoir. It has become synonymous with an environmental catastrophe representing one of the world’s worst ecological disasters (Cai et al., 2003). In the Soviet era, massive quantities of water from Amu-Darya and Syr-Darya were diverted for the irrigation of cotton with a consequent decrease in river water inflow into the Aral Sea (Figure 2). This trend has continued in the post-Soviet era period causing the Aral Sea to shrink dramatically.

In the early 1960s, the Aral Sea had a surface area of about 68,000 km\(^2\) with a capacity of about 1090 km\(^3\) (Micklin, 1988). Consequent to significant diversion of incoming water from the rivers, the sea has now lost almost 90% of its source water and two-thirds of its surface area. At the same time, pesticides applied to agricultural fields have been transported to the inland sea resulting in significant pollution. In addition, the relatively small amount of river water reaching the sea contains elevated levels of salts. Consequently, seawater salinity has increased fourfold. Over the past decade of transition, the Central Asian states have not been able to tackle the root causes of the desertification of the Aral Sea, namely, reducing diversions and increasing flows into the sea.

In addition to widespread land degradation and water quality deterioration, the changes in the Aral Sea and Aral Sea Basin have caused local micro-climate changes. There have been serious negative impacts on human health with higher rates of respiratory diseases from salt and toxic-laden dusts that have been mobilized from the rapidly drying Aral Sea (Fayzieva, 2004) as well as water-borne diseases associated with the use of polluted water. Per capita calorie intake in populations that inhabit the basin has fallen below the average for developing countries. The post-Soviet era has seen the collapse of existing trade arrangements and the abolition of subsidies with significant implications for agricultural outputs. Consequently, the Central Asian countries have been left with the task of developing independent and sustainable market economies. Although there are signs of recovery, agricultural and food production indices still remain between 60 to 90% of the pre-independence level.

Considering the availability of natural and human resources in Central Asia, there is the potential for improving the productivity of agriculture in the region to
meet the food, feed, and fibre demands and to generate employment and additional income opportunities. This paper provides an assessment of the salt-induced land and water resources degradation and associated environmental implications, and proposes response options to improve agricultural productivity under these degraded environments in the Aral Sea Basin in Central Asia.

2. Water resources

The surface water resources of Central Asia are of strategic importance to the countries of the region as economic activities and livelihoods are dependent on them. The larger water resources in Central Asia are trans-boundary rivers, which consist of the following: Syr-Darya and Amu-Darya (Afghanistan, Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan), Chu and Talas (Kyrgyz Republic and Kazakhstan), Tarim (Kyrgyz Republic, Tajikistan, China), Ili (China, Kazakhstan), Irtysh (China, Kazakhstan, Russia), and Ural, Ishim, and Tobol (Kazakhstan, Russia) (Dukhovny and Sokolov, 2005). Of all the rivers, Amu-Darya and Syr-Darya are the major rivers that have a pivotal role in their contribution to the region’s agriculture. The total mean annual flow in Amu-Darya and Syr-Darya Basins is estimated to be 123.08 km³ (Khamrayev, 2005).

The Amu-Darya is the largest river in the region in terms of water resources. The river’s main catchment area is in Tajikistan, from where it flows along the border between Afghanistan and Uzbekistan, crosses Turkmenistan, flows back into Uzbekistan and finally discharges into the Aral Sea in the territory of Uzbekistan. In terms of annual sediment load in the active channel (in excess of 100 megagram, Mg), the Amu-Darya clearly ranks first in Central Asia and is one of the highest in the world. Based on the Glavgidromet datasets, the recently estimated annual surface water resources in the Amu-Darya Basin are presented in Table 1 (Khamrayev, 2005). The total average annual water flow in the basin is estimated at 81.49 km³. This estimate includes surface runoff (both accounted and unaccounted) of 68.29 km³ and groundwater inflow of 0.34 km³. The contributions of other rivers that merge into Amu-Darya at different sections of the main stream and those small rivers from northern Afghanistan and of Turkmenistan are estimated to be 12.86 km³.

Although Syr-Darya is the longest river in Central Asia, its water flow ranks second after Amu-Darya. Its sources are in the Central Tian Shan Mountains. The river is at its fullest in spring and summer, starting in April and reaching a peak in June. Its main catchment area is in the Kyrgyz Republic, from where the river crosses Uzbekistan and Tajikistan and flows into the Aral Sea in Kazakhstan. The total average annual water flow in the Syr-Darya Basin is estimated at 41.59 km³ (Khamrayev, 2005), which is almost half that of the Amu-Darya Basin. This estimate includes surface runoff of 36.96 km³ and groundwater inflow of 1.67 km³ (Table 2). The contribution of other rivers in Kazakhstan to the total flow in the main steam is estimated to be 2.96 km³.

Groundwater is an integral part of the water resources in Central Asian states. In total, 338 aquifers have been identified and categorized according to their hydrodynamic conditions and formation characteristics: 96 in Kazakhstan; 16 in the Kyrgyz Republic; 94 in Uzbekistan; 26 in Tajikistan, and 106 in Turkmenistan. Approximately 30% of these aquifers are shared by two or more Central Asian states (Fayzieva et al., 2004). Total groundwater reserves in the Aral Sea Basin are estimated at 43.71 km³ (Mirzaev and Khamraev, 2000). More than half of these reserves (58%) are located in the Amu-Darya Basin. The total annual renewable groundwater resources in the Aral Sea Basin are estimated at 17 km³, of which net annual extraction for different uses does not exceed 11 km³. There is a decline in the use of groundwater resources because: (1) the cost of

### Table 1. Average annual water resources (km³) in Amu-Darya Basin

<table>
<thead>
<tr>
<th>River – Section</th>
<th>Surface runoff</th>
<th>Groundwater inflow</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accounted</td>
<td>Unaccounted</td>
<td></td>
</tr>
<tr>
<td>Vaksh – Tutkoul</td>
<td>20.29</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>Pyandj – Lower Pyandj</td>
<td>34.02</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Kafirnigan – sum of rivers</td>
<td>5.63</td>
<td>0.12</td>
<td>0.05</td>
</tr>
<tr>
<td>Surkhandarya – sum of rivers</td>
<td>3.77</td>
<td>0.06</td>
<td>0.22</td>
</tr>
<tr>
<td>Sherabad – Sherabad</td>
<td>0.23</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Kunduz – Askarkhana</td>
<td>4.11</td>
<td>0.01</td>
<td>—</td>
</tr>
<tr>
<td>Amu-Darya River (Total)</td>
<td>68.05</td>
<td>0.24</td>
<td>0.34</td>
</tr>
<tr>
<td>Kashkadarya – sum of rivers</td>
<td>1.07</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Zarafshan – Dupuliv</td>
<td>5.29</td>
<td>0.30</td>
<td>—</td>
</tr>
<tr>
<td>Rivers of Afghanistan + Turkmenistan</td>
<td>6.10</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Amu-Darya Basin (Total)</td>
<td>80.51</td>
<td>0.57</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Notes: a Also include Magiandarya – Sudji river systems. b Consists of rivers of northern Afghanistan and small rivers of Turkmenistan. Source: Adapted from Khamrayev (2005).
Table 2. Average annual water resources (km³) in Syr-Darya Basin

<table>
<thead>
<tr>
<th>River – Section</th>
<th>Surface runoff</th>
<th>Groundwater inflow</th>
<th>Total</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accounted</td>
<td>Unaccounted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naryn – Toktogul</td>
<td>14.02</td>
<td>0.40</td>
<td>0.30</td>
<td>14.72</td>
</tr>
<tr>
<td>Fergana Valley rivers</td>
<td>11.89</td>
<td>0.67</td>
<td>0.69</td>
<td>13.25</td>
</tr>
<tr>
<td>Chirchik, Angren, and Keles rivers</td>
<td>8.82</td>
<td>0.30</td>
<td>0.33</td>
<td>9.45</td>
</tr>
<tr>
<td>Midstream rivers</td>
<td>0.36</td>
<td>0.50</td>
<td>0.35</td>
<td>1.21</td>
</tr>
<tr>
<td>Syr-Darya up to Chardara</td>
<td>35.09</td>
<td>1.87</td>
<td>1.67</td>
<td>38.63</td>
</tr>
<tr>
<td>Rivers of Kazakhstan</td>
<td>2.45</td>
<td>–</td>
<td>0.51</td>
<td>2.96</td>
</tr>
<tr>
<td>Syr-Darya Basin (Total)</td>
<td>37.54</td>
<td>1.87</td>
<td>2.18</td>
<td>41.59</td>
</tr>
</tbody>
</table>

Notes: § Also includes lateral tributaries.
Source: Adapted from Khamrayev (2005).

Table 3. Use of available water resources for agricultural, domestic, and industrial sectors in different countries of Central Asia

<table>
<thead>
<tr>
<th>Country</th>
<th>Agriculture use (%)</th>
<th>Domestic use (%)</th>
<th>Industrial use (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kazakhstan</td>
<td>81.8</td>
<td>1.7</td>
<td>16.5</td>
</tr>
<tr>
<td>Kyrgyz Republic</td>
<td>93.8</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Tajikistan</td>
<td>91.6</td>
<td>3.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Turkmenistan</td>
<td>97.5</td>
<td>1.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>93.2</td>
<td>4.7</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Source: FAO (2002).

energy has significantly increased since the 1990s due to increased cost of the electricity in most of the countries; (2) most of the wells installed in the 1970s and 1980s need substantial investment in rehabilitation, which is often beyond the means of most farmers; and (3) groundwater is considered to be a strategic resource for the future and is reserved for the drinking needs of generations to come.

The use of available water resources in terms of percentages diverted for the agricultural, domestic, and industrial sectors of the Central Asian states is presented in Table 3. The allocation of available water resources clearly reflects the importance of the agricultural sector as it draws as much as 91% of the water resources in the region. Among the Central Asian states, Kazakhstan is the only country where the share of agriculture is less than 90% of the total water use. Turkmenistan is amongst the top countries in the world where agriculture draws more than 97% of the water used in different sectors.

Estimates of water use with respect to irrigated area per capita, water use per unit area, and the quantity of water used per unit agricultural production (crop yield) reveal that Turkmenistan has the largest per capita area under irrigated agriculture (0.41 ha per person). Tajikistan has the smallest irrigated area per person (0.11 ha), which is approximately a quarter of that used in Turkmenistan (Nazirov, 2005). The average for all the states is 0.18 ha irrigated area per person (Dukhovny and Sokolov, 2005). Considering the effective use of water in terms of crop production, Uzbekistan and Kazakhstan use about half of the quantities of water to produce the same yield (1,220–1,350 m³ t⁻¹) compared to the quantities of water used in Kyrgyz Republic and Turkmenistan (2,370–2,410 m³ t⁻¹) (Nazirov, 2005).

Although Central Asia is not the driest region of the world, there are water shortages in some areas because of mismanagement in the form of excessive use of water for irrigation and leaching of salts from the soil profile. In addition, there are increasing amounts of water stored for hydropower generation, fish industry, and environmental flows. The limitations of the current policies have become more obvious in the present scenario where the upstream countries have increased hydropower generation at the cost of downstream countries that find it difficult to secure their irrigation needs during critical periods in the summer.

3. Water quality deterioration

Changes in river runoff have direct implications for water quality and salinity conditions vary significantly along the rivers from upstream to downstream. Long-term monitoring of water quality of Amu-Darya and Syr-Darya indicates that in the 1950s, the salinity of these rivers varied intra annually in the range of 0.33 to 0.72 g L⁻¹. These values are within the permissible limits of water to be used for irrigation. Other river water quality parameters such as major cations and anions, organic compounds, pH, and pesticide levels were also within safe limits during the 1950s. Since the 1970s, the levels of salts in river water have increased steadily as a result of a decrease in the flow of Amu-Darya and Syr-Darya and an increase in the discharge of return water, particularly drainage water from irrigation schemes. Consequently, there have been significant increases in river water salinity. For example, water salinity in the Amu-Darya in March 1985 was 0.58 g L⁻¹ in the Kerki section, while it was as high as 2.70 g L⁻¹ in the Kyzyldjar section, indicating more than four times greater levels than that at the Kerki section. The Kyzyldjar section is in the lower reaches of the river.

The same situation has been observed for changes in water quality along Syr-Darya as it has been adversely affected by anthropogenic activities. Agricultural drainage is the major factor affecting water quality in different sections of Syr-Darya Basin. Whereas downstream areas suffer most from water and soil salinity problems, some upstream areas, such as the Fergana Valley, also suffer substantial groundwater salinization. High salinity in river water is also observed in the section located at the outlet from the Fergana Valley, where it remains in the range of 1.2 to 1.4 g L⁻¹ for several months of the year. In the upstream sections, the river water quality is good with salinity levels of 0.3 to 0.5 g L⁻¹. While moving downstream, the water quality deteriorates as the salinity levels in water range from

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1.4 to 1.6 g L\(^{-1}\) in the Chardara section, 1.6 to 2.0 g L\(^{-1}\) in the Kyzl-Orda section, and reach as high as 2.3 g L\(^{-1}\) in the Kazalinsk section.

Although return flow of water to the rivers is an additional reserve for use, it has become a significant source of environmental pollution in the region (Altiyev, 2005). About 95% of return water has its origin in collector-drainages, which contain elevated levels of salts as well as residues of pesticides, herbicides, fertilizers, and other chemicals used in agriculture. It is estimated that annually about 140 million tons of salt are discharged into the drainage water, with 75% originating from irrigation water. The remaining 25% of the total salt load in drainage water is salt that is mobilized through mineral dissolution within the soil profile. Some estimates reveal the average percentage of mobilized salts at 40% of the total salt discharge into the drainage water (Kijne, 2005). About 60% of the total return flow of water is discharged back into the river system, approximately 25% to evaporation depressions, and 15% is reused directly for irrigation. As a consequence of return water disposal to natural depressions, hundreds of water bodies have been formed in the region. Among them, there is the Aydar-Arnasai depression with a capacity of more than 20 km\(^3\), and many other water bodies containing in excess of a few million m\(^3\) of water (Altiyev, 2005). Since these water bodies do not have an outflow, their water quality has been deteriorating every year due to the concentration effect associated with very high levels of evaporation.

The spatial variability in groundwater quality within the Aral Sea Basin has implications for soil and water quality. For example, in Khorezm where Amu-Darya is the main source of groundwater recharge, the entire area is provided with a drainage system and most irrigated land has been turned into groundwater discharge zones. As a consequence, the previously existing fresh groundwater resources have largely disappeared (Jansen, 2004). In addition to typically high levels of salts in drainage water and, in some areas, groundwater resources, a unique type of water quality deterioration exists in some parts of Central Asia, where water used for irrigation contains higher levels of magnesium (Mg\(^{2+}\)) with the Mg\(^{2+}\) to calcium (Ca\(^{2+}\)) ratio greater than 1. For example, the composition of irrigation water in Arys Turkestan zone of southern Kazakhstan reveals Mg\(^{2+}\) to Ca\(^{2+}\) ratios of approximately 1.66, which is narrowed to 0.98 in drainage water (Table 4). A reduction in the fraction of Mg\(^{2+}\) applied in irrigation water points to its adsorption on the cation exchange complex with the consequence that less Mg\(^{2+}\) appears in the drainage water. Any build up in the fraction of Mg\(^{2+}\) on the exchange complex above 30 percent causes the soil to behave like a typical sodic soil, which is characterized by the degradation of soil physical properties. This is a typical case of magnesium-induced soil degradation in many downstream areas in Kazakhstan and, it is anticipated, significant areas of Uzbekistan although it has yet to be quantified. Results of field trials have indicated that all such magnesium-affected soils respond positively to applications of amendments that supply adequate amounts of Ca\(^{2+}\) to mitigate the effects of Mg\(^{2+}\) (Vyshpolsky et al., 2008).

### 4. Land resources

The total land area in the Aral Sea Basin is 155 million ha (Dukhovny et al., 2005). Soil formation processes consist of several layers of quaternary alluvial sediments, which are made up of loam and intercalating layers of sand, gravel and pebbles. In the central part of the Basin, the total thickness of these formations may reach 600 m, gradually reducing towards the edges of the basin against the valley slopes. These alluvial layers represent a freshwater aquifer that is recharged in the mountains and along the mountain slopes through rainfall and infiltration from numerous streams. Upper cretaceous formations are deep and consist of compacted sand, sandstone and some clay. The texture of most soils ranges from silt to loam, with major textural class as silt loam. Other textural classes such as sands and clays are also found in some areas. The organic matter content is low. In terms of nutrient availability status, most soils have low levels of inorganic nitrogen, low potassium, and adequate phosphorus.

Estimates show that about 33 million ha in the Aral Sea Basin are suitable for irrigation (Dukhovny, 2005), indicating that at present only a little over one-quarter of the suitable land is indeed irrigated (Kijne, 2005). A small part of the irrigated agriculture has been developed in areas with sufficient natural drainage. In these areas, the discharge of the entire volume of subsurface drainage water can be disposed of without artificial drainage. These areas are generally found in the topographically elevated zones.
(mountainous slopes and small mountain plains), near draining rivers and close to the Aral Sea. However, in most parts of the Basin, the natural drainage capacity is not sufficient and artificial drainage is needed to supplement the natural drainage.

5. Land degradation

The salinization of land resources in Central Asia has been the consequence of both naturally occurring phenomena and anthropogenic activities causing secondary salinity. The contribution of anthropogenic activities is greater than primary salinity. Excessive irrigation, caused by either lack of information on actual crop water requirements or a recognized need to apply leaching water, has resulted in rising groundwater levels and secondary soil salinization. Nearly half of the region’s irrigated lands are affected by varying levels of salinity (Kijne, 2005). Salt-affected soils are a major impediment to optimal utilization of agricultural production systems. The largest part of salt-affected soils and saline waters exists in the lower reaches of Amu-Darya and Syr-Darya Basins, where salinity is one of the main factors threatening food production. Salinization has been exacerbated by the lack of safe disposal of large volumes of poor-quality drainage water, deep drainage which promotes salt mobilization, the mismatch between demand and supply of irrigation water, and the lack of adequate maintenance of irrigation and drainage networks.

The changes in the extent of salt-affected and waterlogged soils under irrigated agriculture during the past decade (1990–2000) in Amu-Darya and Syr-Darya Basins are presented in Table 5. In 1990, the salt-affected area in the Amu-Darya Basin was 1.16 million ha, which was increased to 1.87 million ha in 2000, an increase of 57% over the 1990 level. Although the area under salt-affected soils in Syr-Darya Basin in 1990 (0.34 million ha) was less than one-third of that in Amu-Darya Basin, the relative increase over the same period is considerably higher with an estimated rate of 79% (0.61 million ha in 2000). It is evident that there has been a substantial increase in the extent of salt-affected land. Similar trends have been observed with the extent of waterlogged soils in both the basins. Considering salt-affected and waterlogged soils together, the rate of land degradation has been greater in Syr-Darya Basin than in Amu-Darya Basin. Since Syr-Darya and Amu-Darya basins constitute a significant portion of the Aral Sea Basin, it is evident that more than 50% of the irrigated area in the basin has been affected by salinization and/or waterlogging, both of which are significant resource degrading processes.

The major part of salt-affected soils in Central Asia falls under the category of saline soils, which are characterized by excessive levels of soluble salts in the root zone. However, there is growing evidence that some areas of salt-affected soils fall under the sodic and saline-sodic category, which is characterized by the presence of sodium ions (Na+) to levels that induce structural instability that is often manifested by slaking, swelling, and dispersion of clay as well as specific conditions that may cause surface crusting and hard-setting (Shainberg and Letey, 1984; Sumner, 1993). These physical impediments affect water and air movement, plant-available water holding capacity, root penetration, seedling emergence, runoff, erosion, tillage and sowing operations. In contrast to sodic conditions, excess salinity levels do not have adverse impacts on soil physical and hydraulic properties. Rather, saline conditions may have favourable effects on soil structural stability (Quirk, 2001). The adverse effects of soil salinity on crop growth stem from two aspects: (1) increases in the osmotic pressure thereby making water in the soil less available for uptake by plants, and (2) specific effects of some elements present in excessive concentrations. Almost all salt-affected soils are characterized by imbalances in plant-available nutrients, which affect plant growth and yield (Naidu and Rengasamy, 1993; Qadir and Schubert, 2002).

In addition to soil degradation stemming from typical categories of salt-affected soils (saline, sodic, and saline-sodic), magnesium-induced soil degradation occurs in some parts of Central Asia. More than 30% of the irrigated area in Kazakhstan is represented by the soils that have exchangeable magnesium percentage (EMP) in the range of 25–45%, and in some cases, as high as 60% (Bekbaev et al., 2005). Excess levels of Mg2+ on the cation exchange complex individually or in combination with Na+ result in soil degradation through impacts on soil physical properties. The major reason for the specific Mg2+ effect is that the hydration energy and hydration radius of Mg2+ are greater than Ca2+ (Bohn et al., 1985). Thus, the soil surface tends to absorb more water than where exchangeable Ca2+ is present, resulting in weakening of the forces that keep soil particles together. This, in turn, decreases the amount of energy required to break down soil aggregates (Oster and Jayawardane, 1998). In addition, high Mg2+ levels in soils tend to increase surface sealing and erosion (Dontsova and Norton, 2002).

Table 5. Extent of salt-induced land degradation and waterlogging (million ha) under irrigated agriculture in Amu-Darya and Syr-Darya Basins over the period 1990 to 2000

<table>
<thead>
<tr>
<th>Land degradation type</th>
<th>Amu-Darya Basin</th>
<th>Syr-Darya Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterlogged soils</td>
<td>1.29</td>
<td>1.57 (22)*</td>
</tr>
<tr>
<td>Salt-affected soils</td>
<td>1.16</td>
<td>1.82 (57)</td>
</tr>
<tr>
<td>Sum of both soils</td>
<td>2.45</td>
<td>3.39 (38)</td>
</tr>
</tbody>
</table>

Notes: * Figures in parentheses indicate percent increase in salt-affected or waterlogged area in 2000 over that in 1990 in the respective land degradation type.

Source: Modified from Dukhovnya (2005).
With low infiltration rates and hydraulic conductivities, magnesium-affected soils are typically referred to as takyr soils in the Central Asian region. Upon drying during the post-irrigation phase, these soils form massive clods, which influence water flow rates. The use of high-magnesium soils and waters for agriculture without suitable management practices has resulted in a gradual decline in cotton (Gossypium hirsutum L.) yields in the affected areas with a concomitant decline in incomes of farmers who are dependent on this crop for their livelihoods (Bekbaev et al., 2005; Karimov et al., 2009).

6. Biophysical response options addressing land and water resources degradation

Considering the widespread salt-induced land resources degradation and water quality deterioration in the Central Asian states, there is a need to address the associated problems at different scales, ranging from biophysical options for the management of the affected natural resources (salt-affected and waterlogged soils and saline waters) for improving agricultural productivity and environment conservation to enhanced interstate cooperation supplemented by appropriate policy and institutional interventions.

Since there is no single biophysical solution to the complex problems of salt-induced soil degradation and waterlogging in Central Asia, approaches addressing the management of salt-affected and waterlogged environments need to be multidimensional and multidisciplinary. These approaches should take into account the biophysical and environmental conditions of the target area as well as livelihood aspects of the communities depending on them. There are several promising examples, which have the potential for large-scale adoption in Central Asian states under government or community-based programs aiming at improved productivity of a range of degraded soils, from abandoned areas due to extremely low or no productivity to those with low productivity of common agricultural crops.

Considering environmental implications in the region partly because of return flow of saline water to the rivers, there are possibilities of reusing this water in areas where it is generated rather than exporting it to another place. Already 15% of saline drainage water is reused directly for irrigation, which can be increased to protect river water quality. There are several studies, which have shown that saline waters are a valuable resource that can be reused for irrigation directly or in conjunction with freshwater depending on the concentration and type of salts (Rhoades et al., 1992; Van Schilfgaarde, 1994; Oster and Grattan, 2002).

The following studies are presented as promising examples revealing that salt-affected and waterlogged soils and saline waters can be transformed from environmental burdens and with economic constraints to opportunities with the potential to shift from subsistence farming practices to income-generating ventures.

6.1. Rehabilitation of abandoned saline lands through crop-based interventions

Rehabilitation of abandoned salt-affected soils through crop-based interventions is an attractive low-cost opportunity that can be undertaken by farmers (Qadir and Oster, 2004; Qadir et al., 2007). The introduction of halophyte species licorice (Glycyrrhiza glabra L.) as a bioremediation crop for the reclamation of saline soils and subsequent restoration of irrigated cropping systems has been studied by Kushiev et al. (2005) on abandoned land in the Hungry Steppes of Uzbekistan. After four years of cropping with licorice, the field was reverted back to a cotton-wheat rotation prevalent in the region. The yields of both crops were significantly higher than the crops grown on adjacent saline fields (Figure 3). Yields of wheat after licorice increased from 0.87 t ha⁻¹ on saline fields to 2.42 t ha⁻¹, revealing nearly a 3-fold increase. Similarly, cotton yields increased from 0.31 t ha⁻¹ to 1.89 t ha⁻¹ with a 6-fold increase due to the remediation affects of licorice. The average yields of wheat and cotton for the Hungary Steppes of Central Asia are 1.75 and 1.5 t ha⁻¹, respectively. The yields of these crops from the bioremediated fields clearly demonstrate the potential of licorice to increase the productivity of abandoned saline fields thereby increasing farm-level incomes and livelihoods of the associated communities.

The rehabilitation of the abandoned saline soils, and in certain cases saline-waterlogged soils, under licorice cultivation is attributed to the combined effect of (1) a decrease in the water table to below 2 m; (2) a decrease in the total salt content of the root zone and soil profile due to enhanced leaching of salts associated with improved soil

![Figure 3. Yields of cotton and wheat after four years of growing licorice compared to an adjacent saline field.](Source: Kushiev et al., (2005)).
hydraulic conductivity and infiltration rate; and (3) an increase in the soil organic carbon content because of the increased root activity and biomass over the 4-year period (Kushiev et al., 2005). This intervention has the potential to rehabilitate waterlogged saline soils in areas with drainage congestion problems. Possibly 0.5 million ha can benefit from licorice cultivation and rehabilitation.

6.2. Introduction of rice in saline areas for salt management and additional income

Winter wheat and cotton have become the dominant components of farming systems in Central Asia with farmers obliged to grow these crops on saline and waterlogged soils particularly in the lower reaches of Syr-Darya and Amu-Darya basins. Consequently, there has been a decrease in the area under rice cultivation (Wegerich, 2001). Current wheat production practices involve growing the crop over the winter with a summer fallow, which results in the movement of salts to the surface due to capillary rise from saline groundwater occurring at a shallow depth. As a result, leaching of salts is undertaken in July–September when water demand for irrigation is at its peak for cotton production in other parts of the region.

Rice is a suitable arable crop for cultivation on saline soils and/or irrigation with saline waters. Higher rates of water application for rice during its growth period also lead to leaching of salts from the root zone for the benefit of the subsequent crops. Such irrigation practices minimize the need for additional water application for leaching of salts from these soils in the latter part of the year. In recent years, there has been consideration of incorporating rice as a summer crop within the winter wheat monoculture system in Khorezm. This can be achieved through the transplanting of 35–40-day-old early maturing rice varieties into flooded fields (Karimov et al., 2006). The rice seedlings are established in a nursery on an area that is sufficient in providing transplanting material for the main field, this being a similar approach as commonly undertaken in transplanted rice based systems of Southeast Asia. By transplanting ‘mature’ rice seedlings, significant savings in water (20–25%) can be achieved when compared to direct sowing of rice seeds. Using such an approach, farmers in Gurlen and Shavat districts of Khorezm region have achieved rice yields as high as 5 t ha⁻¹ (Karimov et al., 2006). An appropriate combination of zero tillage practices and land leveling results in an increase in cropping intensity, greater farm-level productivity, and concurrent decrease in soil salinity levels (Figure 4; Koshekov et al., unpublished data).

Between 1992 and 2000, the area under rice cultivation in Uzbekistan has declined from 182,000 ha to 65,000 ha, equivalent to a 65% decrease with a concomitant decline in rice production (Wegerich, 2001). In the short term, rice could be reintroduced under the aforementioned cropping system to reach 1992 levels of production whilst providing additional income to associated farming communities.

![Figure 4. Effects of growing rice and wheat in rotation along with tillage practices and land leveling on grain yield. The treatment description refers to: TT (wheat–rice rotation using traditional tillage practiced by the farmers); ZT (wheat–rice rotation using zero tillage); TT + LL (wheat–rice rotation using traditional tillage practiced by the farmers along with land leveling); and ZT + TT (wheat–rice rotation using zero tillage along with land leveling).](image)

6.3. Productivity enhancement of high-magnesium soils through calcium supplement

The productivity of magnesium-affected soils can be enhanced by increasing Ca²⁺ on the cation exchange sites to mitigate the effects of excessive exchangeable Mg²⁺ (Karajeh et al., 2004; Vyshpolsky et al., 2008). As a major waste product of phosphorous fertilizer factories, phosphogypsum is a low-cost source of Ca²⁺ that can be used as an amendment for magnesium-affected soils. In addition to increasing the Ca²⁺ content of the soil, phosphogypsum supplies appreciable quantities of phosphorous to the soil (Alcorde and Rechcigl, 1993). Other low-cost soil amendment supplying Ca²⁺ is mined gypsum (CaSO₄·2H₂O).

Based on the results of a 4-year study conducted in Kazakhstan on magnesium-affected soils, Vyshpolsky et al. (2008) demonstrated the beneficial effects of applying a source of Ca²⁺ (phosphogypsum) to these soils in terms of improvement in soil quality and cotton yield. The irrigation water used at the study site was of marginal-quality with Mg²⁺ to Ca²⁺ ratio ranging from 1.30 to 1.66 during cotton growing season. There were three treatments: (1) control without phosphogypsum application; (2) soil application of phosphogypsum at the rate of 4.5 t ha⁻¹; and (3) soil application of phosphogypsum at the rate of 8.0 t ha⁻¹. The amendment was applied to the respective treatments once at the beginning of the study. Its application increased Ca²⁺ concentration in the soil and triggered the replacement of excess Mg²⁺ from the cation exchange sites. After harvesting the first crop, there was an 18% decrease in exchangeable magnesium percentage (EMP) in the upper 0.2 m soil depth over the pre-experiment level in plots where phosphogypsum was applied at 4.5 t ha⁻¹, and 25% decrease in EMP in plots treated with phosphogypsum at...
Table 6. Exchangeable magnesium percentage (EMP) levels in the soil as affected by the application of phosphogypsum

<table>
<thead>
<tr>
<th>Soil depth</th>
<th>Exchangeable magnesium percentage (EMP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phosphogypsum at 4.5 t ha(^{-1})</td>
</tr>
<tr>
<td></td>
<td>Initial soil</td>
</tr>
<tr>
<td>0.0–0.2 m</td>
<td>28(^a)</td>
</tr>
<tr>
<td>0.2–0.4 m</td>
<td>33</td>
</tr>
<tr>
<td>0.4–0.6 m</td>
<td>35</td>
</tr>
</tbody>
</table>

Notes: \(^a\) EMP = 100 (\(E_{Mg}\)) (CEC where both \(E_{Mg}\) and CEC (sum of exchangeable cations) expressed as cmol, kg\(^{-1}\). \(^b\) Percent decrease (–) over the respective initial EMP level at a specified soil depth.

Source: Adapted from Vyshpolsky et al. (2008).

Figure 5. Cotton yield as affected by different rates of phosphogypsum application (0, 4.5, and 8.0 t ha\(^{-1}\)) on a magnesium-affected soil in Kazakhstan. The error bars indicate standard error of means of three replications.

Source: Adapted from Vyshpolsky et al. (2008).

8 t ha\(^{-1}\) (Table 6). The additional beneficial effect of the amendment application resulted in an increase in the soil phosphorus content.

The highest cotton yields were obtained during the first year of the treatment application, which were 2.7 and 3.0 t ha\(^{-1}\), respectively, from the treatments where phosphogypsum was applied at 4.5 and 8 t ha\(^{-1}\). Cotton yield in the control plots (1.4 t ha\(^{-1}\)) was almost half the yield harvested from phosphogypsum treatments. There was a 93% increase in cotton yield from the phosphogypsum treatment (4.5 t ha\(^{-1}\)) over the control. In the case of the 8.0 t ha\(^{-1}\) treatment, cotton yield increased to 114% over that harvested from control plots (Figure 5). The 4-year average cotton yield with phosphogypsum application at 8 t ha\(^{-1}\) was 2.6 t ha\(^{-1}\), while it was 2.4 t ha\(^{-1}\) when phosphogypsum was applied at 4.5 t ha\(^{-1}\). The control plots yielded cotton at 1.4 t ha\(^{-1}\).

The increase in cotton yield in phosphogypsum treatments was due to the increased levels of Ca\(^{2+}\) in soil solution and on cation exchange sites, thereby improving the ionic balance and physical properties of the soil. The increase in phosphorus levels from the amendment application also helped in improving the phosphorous nutrition of the plants. Since phosphogypsum was applied once at the beginning of the study, exchangeable Mg\(^{2+}\) levels tended to increase after four years of application, particularly in the treatment with 4.5 t ha\(^{-1}\) phosphogypsum. This necessitated the need for a booster dose of phosphogypsum to such soils after every 4–5 years to optimize the ionic balance and sustain higher levels of cotton production. The economic benefits from the phosphogypsum treatments were almost twice that of the control. In the short term, the ‘phosphogypsum’ technology has the potential to improve the productivity of about 150,000 ha affected by magnesium-induced soil degradation in southern Kazakhstan. In the medium and long term, the use of Ca\(^{2+}\) supplying amendments can be expanded to other areas in the Central Asian states where growing evidence suggests a gradual increase in exchangeable Mg\(^{2+}\) levels in soils.

6.4. Use of tree species as biological pumps to lower elevated groundwater levels

Near-horizontal subsurface drainage systems have been used in the Aral Sea Basin to address waterlogging and salinity problems. These systems consist of a combination of horizontal buried pipes and deep open drains. Previous experience had shown that these systems although having distinct advantages had negative implications such as the need for proper reuse or disposal of saline drainage water, high maintenance cost, and the fact that a portion of highly fertile land is taken out of production due to the presence of drains. In the case of reusing saline drainage effluent for irrigation without salinity management interventions, salts tend to redistribute in the landscape. The disposal of saline drainage effluent into river systems was reported to cause pollution of natural water bodies in a gradual manner (Heuperman et al., 2002). In addition, a substantial part of the installed drainage systems in Central Asia is partly or fully non-functional because of the lack of finance on the part of farmers and the government.

As a potential alternative to a cost-intensive horizontal drainage system, a plant-based approach ‘bio-drainage’ can be used to control elevated levels of groundwater in certain areas. Studies carried out on bio-drainage have shown promising results (Patil et al., 1994; Tomar et al., 2003; Khamzina et al., 2006). Collaborative research of Center for Development Research, Germany and Uzbek Forestry Research Institute at the Khiva Research Station evaluated 10 native and exotic tree species for their transpiration rate and salinity resistance. The species included: apricot (Prunus armeniaca L.), black poplar [Populus nigra var. pyramidalis (Rozan) Spach], black willow (Salix nigra Marshall), Chinese cedar [Biota orientalis (L.) Franco],...
Table 7. Mean daily leaf transpiration rates (mmol m\(^{-2}\) s\(^{-1}\)) of various tree species recorded months after planting (MaP) on two soil types

<table>
<thead>
<tr>
<th>Tree species</th>
<th>7 MaP</th>
<th>14 MaP</th>
<th>16 MaP</th>
<th>18 MaP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. bignonioides (42)</td>
<td>2.11</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>E. angustifolia (53)</td>
<td>2.11</td>
<td>4.51</td>
<td>5.12</td>
<td>9.99</td>
</tr>
<tr>
<td>F. pennsylvanica (48)</td>
<td>2.46</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>M. alba (52)</td>
<td>2.22</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>P. armeniaca (48)</td>
<td>2.20</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>P. euphratica (48)</td>
<td>2.22</td>
<td>3.3</td>
<td>4.82</td>
<td>8.32</td>
</tr>
<tr>
<td>P. nigra var. pyramidalis (44)</td>
<td>2.43</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>P. nigra (44)</td>
<td>2.30</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>U. pumila (52)</td>
<td>2.28</td>
<td>3.3</td>
<td>4.53</td>
<td>9.22</td>
</tr>
<tr>
<td>Loamy site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. bignonioides (106)</td>
<td>2.12</td>
<td>—</td>
<td>4.38</td>
<td>6.69</td>
</tr>
<tr>
<td>E. angustifolia (171)</td>
<td>2.68</td>
<td>4.37</td>
<td>9.12</td>
<td>9.39</td>
</tr>
<tr>
<td>F. pennsylvanica (118)</td>
<td>2.36</td>
<td>—</td>
<td>7.13</td>
<td>7.86</td>
</tr>
<tr>
<td>M. alba (108)</td>
<td>2.79</td>
<td>2.64</td>
<td>6.51</td>
<td>7.46</td>
</tr>
<tr>
<td>P. armeniaca (69)</td>
<td>2.40</td>
<td>—</td>
<td>5.15</td>
<td>4.48</td>
</tr>
<tr>
<td>P. nigra var. pyramidalis (99)</td>
<td>2.50</td>
<td>—</td>
<td>2.99</td>
<td>6.04</td>
</tr>
<tr>
<td>P. nigra (115)</td>
<td>2.40</td>
<td>—</td>
<td>7.31</td>
<td>5.7</td>
</tr>
<tr>
<td>U. pumila (150)</td>
<td>2.62</td>
<td>3.63</td>
<td>7.38</td>
<td>9.49</td>
</tr>
</tbody>
</table>

Notes: * Figures in parentheses indicate the number of cases for a particular tree species.
Source: Modified from Khamzina et al. (2006).

Euphorbes poplar (Populus euphratica Olivier), Russian olive (Elaeagnus angustifolia L.), salt cedar (Tamarix androssovii), Siberian elm (Ulmus pumila L.), swamp ash (Fraxinus pennsylvanica Marshall), and white mulberry (Morus alba L.). The transpiration rates per unit leaf area (LA) varied with time, i.e. months after planting (MaP) and followed the sequence: 18 MaP (late season) >16 MaP (mid growing season) >14 MaP (early season) >7 MaP (end of the first season) (Table 7), which were consistent with the mean air temperature and relative humidity during these periods (Khamzina et al., 2006).

The calculated seasonal evapotranspiration (ET) for the growing season April–October varied depending on tree species and age. The maximum seasonal ET of over 2,000 mm was estimated for 3-year-old E. angustifolia. The seasonal ET of U. pumila approached 1,600 mm. The maximum ET of P. euphratica was as high as 940 mm.

Leaf transpiration rates of three-year-old trees significantly varied among species. Transpiration rates of tree species grown at sites with two soil textures and heterogeneous young stands. The leading tree species with regard to their water use, root growth, and adaptability to the natural environment were found to be E. angustifolia followed by U. pumila, P. euphratica and P. nigra var. pyramidalis, whereas fruit species such as P. armeniaca and M. alba, though desirable from the farmer’s economic viewpoint, showed low bio-drainage potential. However, since the N-fixing E. angustifolia and U. pumila have also superior feed and firewood characteristics, they are expected to add value, which makes them the most suitable candidates for afforestation and bio-drainage purposes.

Other studies on bio-drainage in the Syr-Darya province of Uzbekistan with the Uzhek Forestry Research Institute and the International Center for Agricultural Research in the Dry Areas (ICARDA) have addressed the efficacy of different ages of tree plantations in regulating the groundwater level. Tree plantations reducing evaporation from soil through their crown reduced capillary rise of saline groundwater to the upper soil depth. Salt accumulation was partially restricted, while higher evaporation rates from bare soil in control treatments brought soluble salts to within 0.3 m from the soil surface (Yuldashev, 2008; personal communication).

The desiccated bed of the Aral Sea has become one of the major sources of active wind erosion, which affects 56% of the irrigated area in Uzbekistan, posing a risk for land degradation. It has been estimated that during strong dust storms as much as 1.5–6.5 t ha\(^{-1}\) of dust containing 0.3–1.0 t ha\(^{-1}\) toxic salts are blown away from the desiccated Aral Sea bed and deposited on adjacent lands (UNEP and Glavgidromet, 1999). Khorezm, along with neighbouring Karakalpakstan, is the largest populated area exposed to the wind-borne implications of the Aral Sea disaster (Khamzina, 2006). Salt tolerant crop- and tree-based interventions have the potential to provide a ground cover, thereby reducing the movement of toxic salts. Taking into account the above mentioned aspects, ‘bio-drainage’ technology in the short term has the potential to improve the productivity of 56% of irrigated lands in Uzbekistan, that are subjected to wind erosion, and are imposing risks for land degradation.

6.5. Optimal use of fertilizers to manage effects of water and soil salinity

Optimal use of fertilizers, particularly those supplying nitrogen, can mitigate the adverse effects of soil or irrigation water salinity. Results of a 2-year study in Kazakhstan under farmers’ field conditions reveal that the application of nitrogen at the rate of 140 kg ha\(^{-1}\) can increase cotton yields by a margin of 300 kg ha\(^{-1}\) over nitrogen application rates at 70 kg ha\(^{-1}\) when saline water was used for irrigation. The differences between the treatments were more pronounced when water of higher levels of salinity was used as a source of irrigation (Magay, 2008; personal communication).

Studies conducted elsewhere reveal that split applications of nitrogen to salt-affected soils and/or while using saline waters for irrigation, minimizes the nitrogen losses such as ammonia volatilization from the fields (Gupta and Abrol, 1990). The use of three equal splits at 40 kg ha\(^{-1}\) of the recommended rate of nitrogen (120 kg ha\(^{-1}\)) for rice and wheat was found to be an efficient practice on sodic soils of Uzbekistan.
the Indo-Gangetic Basin (Swarup, 1998). Considering the scope of increasing the reuse of saline drainage water from a mere 16% of the total volume produced in Central Asia, optimal use of fertilizers has the potential to improve water productivity over the long term.

6.6. Mulching of furrows under saline conditions to reduce evaporation

Reduction in evaporation losses under irrigated agriculture is particularly important to minimize salt accumulation in the root zone when saline water is used for irrigation. The results of a 3-year study undertaken in Syr-Darya district of Uzbekistan addressing the interactive effects of saline water irrigation and mulching of furrows demonstrated the beneficial effects of mulching in the form of a better crop response as well as management of root zone salinity. On average, mulched plots used 13 percent less water and produced 12 percent higher yields as compared to non-mulched plots. The significant increase in cotton yield in mulched plots was attributed to increased crop transpiration as a result of reduced salinity in the soil profile. The average root zone salinity was decreased by 13% as compared to non-mulched plots (Mirhashimov et al., unpublished data).

Long-term use of mulching has the potential to further improve soil organic matter content and nutrient availability status, with beneficial effects on crop yield and soil quality. With improved soil conditions, there would be a possibility of irrigating with water of relatively higher salt concentration in a cyclic mode with low-saline water, i.e. using low-saline water at the early stages of cotton development and highly-saline water for irrigation during the second half of the crop growing season, when plants are more tolerant to ambient levels of salinity in the root zone.

6.7. Biomass and renewable energy production using multipurpose plant species

Abandoned salt-affected lands bear a larger potential for biomass and renewable energy production. A strategic move towards renewable energy generation on salt-affected soils and possibly with saline water resources could consider the establishment of plantations consisting of multipurpose tree and shrub species (Khamzina et al., 2008; Qadir et al., 2008). Recent evidence reveals several plant species for renewable energy production on salt-affected environments. For example, in the Amu-Darya River Basin, multi-purpose tree plantations established on degraded land at 2300 stems ha$^{-1}$ produced the energy equivalent of 6.4–10.3 t oil and 12.6–20.5 t coal ha$^{-1}$ five years after planting (Lamers and Khamzina, 2008). The performance of three tree species was in the order: Populus euphratica Oliv. > Elaeagnus angustifolia L. > Ulmus pumila L (Table 8). These plantations provided wood, high quality leaf fodder, fruits and all together contributed to meeting requirements of rural households in the study area of Uzbekistan. (Lamers and Khamzina, 2008). The selected tree species used in these studies were representatives of the local flora, underlining that their promotion would not cause adulteration of the local plant biodiversity.

Other studies have shown that several plant species have the potential to produce renewable energy from salt-affected environments (Pramanik, 2003; Meher et al., 2006; Dagar et al., 2006; Qadir et al., 2008). The cultivation of multipurpose plant species on salt-affected waste lands offers an opportunity to put otherwise unproductive land back into production, but ensures simultaneously that no natural ecosystems are converted into systems for renewable energy production. Also, such conversions may contribute to building up soil carbon stocks and reduce the impact of global warming.

6.8. Complementary approaches facilitating soil and water management

Excessive drainage flows in Central Asian states are an inevitable consequence having off-site impacts. However, farming communities in Central Asia are not fully aware of the consequences of the inappropriate management of drainage flows. In addition, they have no economic incentive to consider the effects of the drainage flows on other areas and farmers, to minimize deep percolation, or to reuse or dispose of drainage flows safely. Under such conditions, it is likely that the bulk of the damage is borne by other farmers and other water users. There is therefore a need for appropriate regulatory policies and investments designed to aid the introduction of improved management practices and decisions. It is likely that a combination of different management instruments will be needed to reduce deep percolation losses and drainage flows, in order to protect surface and groundwater bodies, particularly in downstream areas. There is a need for collective action by different stakeholders to address such issues to minimize the development of secondary salinity and sodicity in the region.
The following aspects are expected to add value to the soil-based interventions: (1) preparation of datasets and maps of soil salinity, sodicity, and waterlogging (indicating their extent and intensity) to determine feasibility of the management options; (2) establishment of benchmark monitoring sites to evaluate changes in salt-affected and waterlogged soils through satellite imagery; (3) improvement in salt tolerance of the genotypes of major field crops such as wheat and cotton through selection, breeding, and molecular and biotechnological options; (4) conservation of potential genetic pools of halophytic plant communities for highly salt-affected environments; (5) introduction of salt-tolerant medicinal and aromatic plant species as income generating options from salt-affected soils; (6) retirement of lands to permanent vegetation where it is not economically feasible to use the degraded lands and/or highly saline waters for crop production; and (7) develop efficient water management measures and practices in the “problem solution area” upstream to reduce the impact on downstream end water farms (source reduction approach).

Some complementary and synergistic approaches proposed for salt-affected soils are also applicable to the management of saline waters. Additional aspects are given below: (1) water quality monitoring networks to monitor temporal and spatial changes in water quality important for agriculture, environment, and human consumption; (2) optimization of the use of freshwater resources by avoiding excessive irrigation over and above the irrigation/leaching rates recommended for the area to maintain salt balances in the soil; (3) development of production systems based on salt-tolerant plant species using saline waters in areas where these waters predominate and disposal options are limited; (4) use of computer models to evaluate the potential of using different saline water irrigation approaches by generalizing site-specific results to similar locations, and (5) establish regional on-demand water supply flexibility options.

7. Enhanced interstate cooperation and appropriate policies and institutions

Several key issues relating to natural resource management in the Central Asian states have been in the limelight since the early 1990s. Soon after their independence, the states responded quickly to the need for a new legal basis for water allocations. The Ministers of Water of the newly independent states jointly declared in September 1991 that water resources management in the Aral Sea Basin would be on the basis of equity and joint benefits. An interstate agreement in February 1992 reflected this commitment by establishing an Interstate Commission for Water Coordination (ICWC). The commission was made responsible for the development of water management policies and management of the annual water allocations for each state and the schedules for the operation of reservoirs. River Basin Organizations were maintained and given the task of carrying out ICWC decisions. The decisions of ICWC have to be unanimous and then are immediately binding for all the states. The Scientific Information Center (SIC) of ICWC undertakes scientific activities and research, prepares proposals, and ensures data exchange between the states. There are other initiatives in the region such as The Aral Sea Basin Program (ASBP), the Interstate Council of the Aral Sea (ICAS), the International Fund for the Aral Sea (IFAS), and the Sustainable Development Commission (SDC). There is some overlap in the activities of these initiatives.

Considering the large number of interstate initiatives as well as involvement of the international community and donor organizations, the management of international waters of the Aral Sea Basin has not been improved in the sense of major breakthroughs. Most importantly, peace over water has been maintained. As in all interstate efforts, the success depends on what the states actually do in their territories. Regional action is therefore mainly a matter of coordination, stimulation, and support for national actions. Such action becomes weak without full support in the form of related national policies, legislations, and their implementations. Some states have advantage over others in having a major portion of the water resources in their territories. However, the upstream ‘supplier’ states, such as Kyrgyz Republic, Tajikistan and southeast Kazakhstan, and the downstream ‘user’ states Turkmenistan, Uzbekistan and southwest Kazakhstan find themselves increasingly in competition for the water resources available in the region.

Each state in Central Asia has its own water and environment policy with the provision of clean drinking water as the topmost priority. As national environmental services struggle with severe budget constraints and difficulties of implementation and enforcement, there are major differences among the states for priority settings to address natural resource management, the environment, and human health. For example, the rehabilitation of the disaster zone around the Aral Sea is the major burden for three states, viz. Kazakhstan, Uzbekistan, and Turkmenistan. These states have spent huge amounts — estimated at US$ 650 million per year — on efforts for socio-economic and environmental stabilization. The economic and environmental potential of joint regional action in soil and water conservation has not yet been fully appreciated.

There is a shortage of skilled manpower, such as modern technology practitioners, in the Central Asian states to address the complex issues of land and water resources management and environment conservation. Successful drainage and soil rehabilitation projects need to contain an array of interventions and improvements, including capacity building for farmers, researchers, and regulatory institutions. Where necessary, these projects should also contain a research component for community-based management of land and water resources to help strengthen

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linkages among researchers, farm advisors, and farmers. Site selection for the rehabilitation projects should take into account the presence of government institutions willing to contribute to the change processes. The effects of these projects are expected to be slow. The degradation of land resources and water quality deterioration is expected to continue where no project has yet been started. Therefore, increased investments on research and technology development leading to the use of natural resources are needed to maximize the benefits for communities and to minimize the adverse environmental impacts. In addition, the development of alternative livelihoods and off-farm employment is expected to remain important. The challenge for achieving sustainable agriculture production systems and livelihoods lies with the establishment of planned and well-coordinated changes at the national as well as interregional levels. Thus, anticipating the interstate cooperation and appropriate supportive policies at the national level as well as the availability of natural resources, there is huge potential for improving the productivity of agriculture in the region to meet national food demands and to generate employment and additional income opportunities.

Finally, for example, farmers alone cannot tackle the huge task of rehabilitating salt-affected degraded soils and making use of best management practices for reusing saline water for irrigation. Therefore, governments should take the lead in preparing strategic plans to improve the quality of research and extension services. This goal can be achieved by opening a dialogue with farming communities, researchers, and policy makers, to improve their understanding of the problem and its future implications at the local, national, and regional scales. The management options for salt-affected soil and saline water resources built on the accumulated wisdom of relevant stakeholders will assist in the adoption of conservation measures at the community level. Such participatory approaches would create a sense of ownership among the farmers and help in strengthening linkages among farmers, researchers, and policy makers.

8. Conclusions

Salt-induced land and water resources degradation in Central Asia is the consequence of both naturally occurring phenomena (primary salinity) and anthropogenic activities causing secondary salinity. The contribution from anthropogenic activities is greater than primary salinity. For example, excessive irrigation rates, lack of safe disposal of large volumes of saline drainage water, the mismatch between demand and supply of irrigation water, and inadequate maintenance of irrigation and drainage networks have resulted in rising groundwater levels and secondary soil salinization. More than half of the region’s irrigated lands are affected by varying levels of salinity and waterlogging. The largest extent of salt-affected soils and saline waters occurs in the lower reaches of the Amu-Darya and Syr-Darya Basins, where salinity is one of the main factors threatening food production and rural livelihoods.

Considering the extent of salt-induced land and water resources degradation in the Central Asian states, there is a need to address the associated problems at different scales, ranging from biophysical interventions for the management of the affected natural resources for improving agricultural productivity and the environment to enhanced interstate cooperation supplemented by appropriate policy and institutional interventions. Since there is no single biophysical solution to this complex problem of salt-induced soil degradation and waterlogging in Central Asia, approaches addressing the management of salt-affected and waterlogged environments need to be multidimensional and multidisciplinary. These approaches should take into account the biophysical and environmental conditions of the target area as well as livelihood aspects of the communities depending on them. As discussed above, there are several promising interventions, which have the potential for large-scale adoption in Central Asian states under government or community-based programs aiming at improved productivity of a range of salt-affected degraded lands and saline waters.

Although the Central Asian states responded quickly to the need for a new legal basis for water resources management on the basis of equity and joint benefits, the management of international waters of the Aral Sea Basin has not been improved. Some states have advantages over others in having a major portion of the water resources in their territories. However, the upstream ‘supplier’ states, such as Kyrgyz Republic, Tajikistan and southeast Kazakhstan, and the downstream ‘user’ states Turkmenistan, Uzbekistan and southwest Kazakhstan find themselves increasingly in competition for the water resources available in the region. There is also a shortage of skilled manpower, such as modern technology practitioners, to address the complex issues of salt-induced land and water resources management and environment conservation. Successful drainage and soil rehabilitation projects need to contain an array of interventions and improvements, including capacity building for farmers, researchers, and regulatory institutions. These projects should also contain a research component for community-based management of land and water resources to help strengthen linkages among researchers, farm advisors, and farmers. Farmers alone cannot tackle the huge task of rehabilitating salt-affected degraded soils and making use of best management practices for reusing saline water for irrigation. In addition to researchers, the involvement of non-governmental organizations and farmers’ associations is important to address long-term sustainable water and salt management; water allocation among users; and minimization of salt loads and accepted interregional plans for its disposal. There are two matters of interest when it comes to irrigation
and salt management, i.e. increased amounts of food produced through irrigation and salt disposal problems that this use of water generates.

The challenge for achieving sustainable agriculture production systems and livelihoods lies with the establishment of planned and well-coordinated changes at the national as well as interregional levels. Thus, anticipating the interstate cooperation and appropriate supportive policies at the national level, there is considerable potential for improving the productivity of agriculture in the region to meet national food demands and to generate employment and additional income opportunities.

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