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RESOURCE RECOVERY & REUSE SERIES 5

5

Potential Business Opportunities from Saline Water and Salt-affected Land Resources

Manzoor Qadir, Andrew D. Noble, Fawzi Karajeh and Biju George

UNITED NATIONS UNIVERSITY UNU-INWEH Institute for Water, Environment and Health

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ICARDA Science for Better Livelihoods in Dry Areas

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SUMMARY

Generally, saline water and salt-affected lands are considered to suffer from low agricultural productivity and significant environmental constraints. However, recent evidence suggests that by recycling and reusing saline water until it becomes inoperable for any economic activity and by returning salt-affected irrigated areas to higher levels of production, a significant contribution to food, feed and renewable energy production could be achieved without expanding the production area and obviating the associated challenges that this brings.

This report delivers four case studies on saline water recycling and reuse by providing the following examples from developed and developing countries: (1) concentration of salts in a sequential manner for effective management of saline drainage water combined with income-generating crops and aquaculture as well as potable water and industrial salt production; (2) production of decentralized and renewable energy by using microhydro-turbines along the natural flow of saline water in drainage water collector networks; (3) profitable horticulture by harnessing solar energy for seawater desalination to produce freshwater for greenhouse irrigation; and (4) large-scale drainage water reuse in the Nile Delta with mixed benefits, challenges and opportunities. Concomitantly, the following examples are given on reversing and restoring salt-affected irrigated land: (1) use of phosphogypsum to mitigate magnesium effects in magnesium-affected lands and to enhance crop productivity; (2) phytoremediation of highly saline abandoned land by growing salt-tolerant shrubs; (3) planting multipurpose salt-tolerant tree species on salt-affected wastelands for biomass and bioenergy production; and (4) large-scale amelioration of sodic soils via gypsum application supported by a number of coordinated actions involving relevant stakeholders.

These examples vividly suggest that strategic investments in salt-affected irrigated zones can make a significant contribution to poverty reduction, generate additional economic benefits and ensure equitable social development for smallholders and marginalized groups, among other advantages. There is a need for a paradigm shift towards *reuse* of saline water until it becomes unusable for any economic activity rather than its *disposal*, and *restoration* of salt-affected soils rather than their *retirement*. In doing so, there are additional gains in the form of regenerating degraded agricultural ecosystems and mitigating climate change impacts through enhanced soil carbon sequestration and ensured food security without significant lateral expansion of the agricultural area. Therefore saline water and salt-affected lands cannot be considered as redundant and consequently neglected, especially in areas that are heavily dependent on irrigated agriculture where significant investments have already been made in infrastructure such as water conveyance and delivery systems to supply water for irrigation and food security.

INTRODUCTION

Since antiquity irrigation has played a key role in feeding the expanding global population and is expected to play a critical role in meeting future agricultural demands. The global area of agricultural land under irrigation has expanded substantially, particularly in the second half of the twentieth century. Between the mid-1960s and the mid-1980s, expansion of irrigation accounted for more than 50% increase in global food production (El-Ashry and Duda, 1999; Hanjra and Qureshi, 2010). Although only about 20% of the world's cropland is currently irrigated, it produces approximately 40% of the food and fiber harvested (Thenkabail et al., 2010).

Long-term sustainability of irrigated lands remains a challenge as irrigation impacts land and water resources in ways that can lower farm productivity over time, particularly in arid and semiarid areas where most irrigation takes place. Irrigation in these areas inevitably degrades water quality in downstream reaches, as dissolved salts enter irrigation return flows, thus increasing the salinity of watercourses from which other farmers and communities draw their water supplies (Wichelns and Qadir, 2015). The same applies to irrigated lands where salts accumulate in the root zone as plants take up 'pure' water and concentrate the salts in the soil profile. Consequently drainage of irrigated landscapes is necessary to remove excess salts, whether through natural drainage systems or artificially through a network of internal and open drains that is common in well-designed irrigation systems (Oster et al., 2012; Oster and Wichelns, 2014).

Although salinity-related problems in irrigated areas in arid and semiarid zones are inevitable, measures on how to prevent or overcome them have been known for some time (Hilgard, 1893); however problems persist in many regions and river basins where farmers apply excessive irrigation water. In this context, the investments needed to provide adequate salt management and drainage solutions are not being made (Janmaat, 2004; Aslam and Prathapar, 2006; Qureshi et al., 2008). With persistent use of irrigation without appropriate salt and drainage management, water quality continues to deteriorate and agricultural land gradually degrades with the elevated levels of salts (Oster et al., 2012).

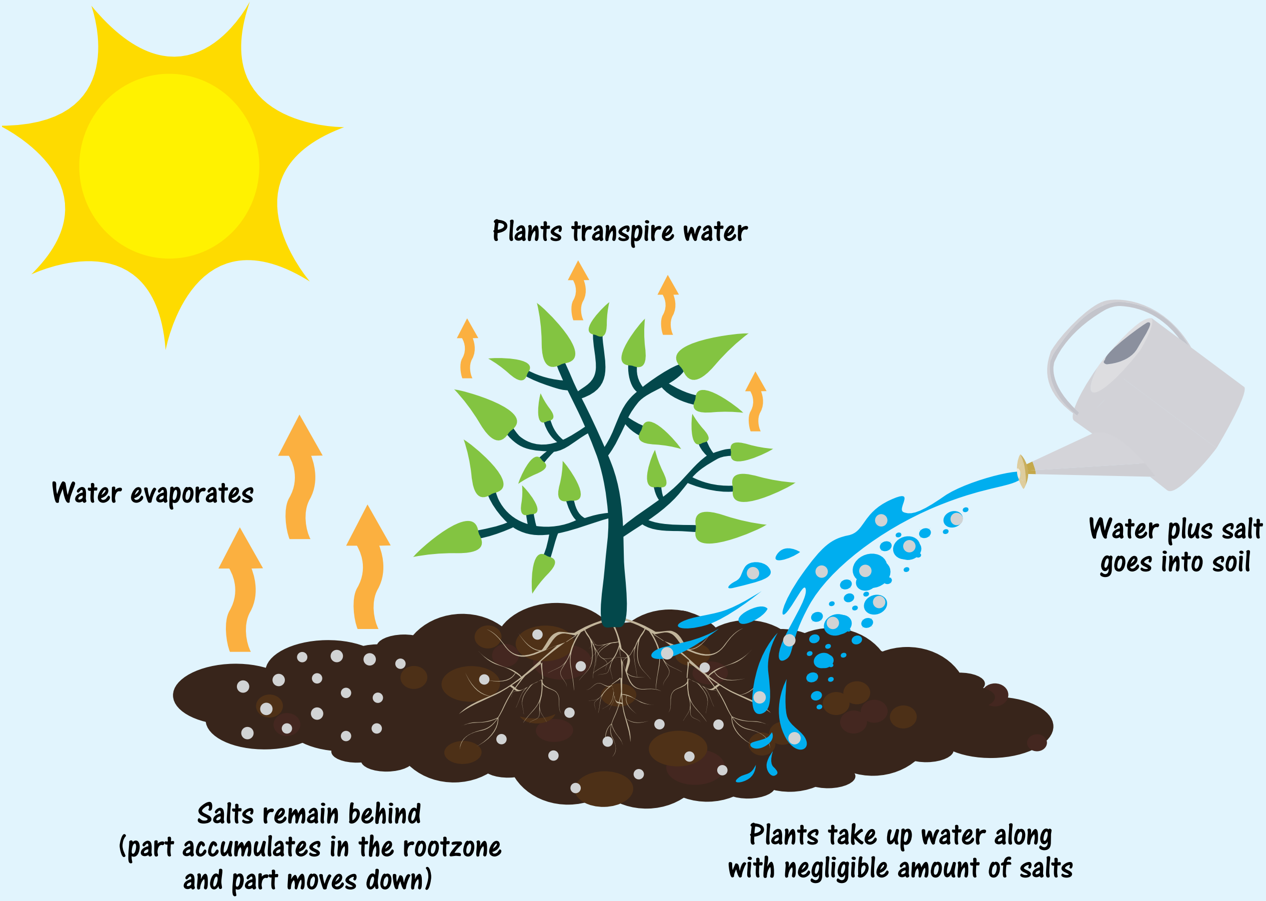
Currently, salt-affected soils occur within the sovereign borders of at least 75 countries (Qadir et al., 2014). The extent of salt-affected soils in irrigated areas has increased in the last two decades (Metternicht and Zinck, 2003), i.e. from 45 million hectares (ha) in 1990 (Ghassemi et al., 1995) to 62 million ha in 2013 (Qadir et al., 2014). Simple extrapolation suggests that every day an area of about 2,000 ha of irrigated cropland is affected by varying levels of salinity (Qadir et al., 2014).

Salt is a component in all water resources, including freshwater or so-called good-quality water (Box 1). All irrigation systems generate drainage water that is laden with salts. The challenge for most irrigation systems is minimization of drainage volume and disposal of salt-laden drainage waters, which are the consequence of irrigation at the system level. Often these saline waters are led off to evaporation ponds without reusing them, which wastes a valuable resource. While these waters are often viewed as a 'problem', it is proposed that these waters could represent an 'opportunity' by adding value to them and their constituents. The same applies to salt-affected lands as those with elevated levels of salts are invariably abandoned resulting in displacement of communities in the location over time.

BOX 1. SALT ADDITION TO THE ROOT ZONE VIA IRRIGATION WATER.

A common source of salts in irrigated soils is the irrigation water itself. All waters, including freshwater used for irrigation, contain salts. After irrigation, the water added to the soil is used by the crop or evaporates directly from the moist soil, leaving the added salt behind in the soil. If it is not removed, it accumulates first in the root zone and then in lower soil depths leading to salt-induced land degradation.

Contrary to the general perception that freshwater contains negligible amount of salts, irrigation with freshwater contributes significant amounts of salt to the soil. For example, irrigation at 6,000 m^3/ha to grow a crop like maize (Brouwer et al., 1985) with freshwater electrical conductivity commonly in the range of 0.3-0.5 dS/m would add 1.1-1.9 tons (t) salt/ha to the soil. Because of higher rates of evaporation and transpiration, salt accumulation in irrigated soils in dry and hot areas tends to be greater than other areas. This necessitates the management of salts added via irrigation through leaching and drainage water collection and their disposal or reuse to avoid on- and off-site salinity effects – this could be viewed as the irrigation-drainage-salinity nexus.



Salt accumulation mechanisms in the root zone of an irrigated area

Considering the scarcity of good-quality water resources and the limited availability of new productive land in irrigated areas in arid and semiarid zones, there is a need to enhance the productivity of marginal-quality water and land resources, such as saline water and salt-affected lands (Qadir and Oster, 2004). Saline water and salt-affected lands cannot be considered as redundant and consequently neglected, especially in areas that are heavily dependent on irrigated lands where significant investments have already been made in infrastructure such as water conveyance and delivery systems to supply water for irrigation and food security.

Focusing on saline water and salt-affected land resources and based on the relevant literature available, this report comprises: (1) case studies concerning options for economic benefits derived from utilizing saline water and reversing salt-induced land degradation in irrigated areas; (2) identification of challenges in large-scale adoption of these options; and (3) potential options to address these challenges.

SALINE WATER AND SALT-AFFECTED LAND RESOURCES

Saline water or salt-prone water is a generic term that usually includes saline (excess of soluble salts), sodic (excess of sodium ions) and saline-sodic (excess of both salts and sodium ions) water resources. In irrigated areas, these water resources generally consist of drainage water generated by irrigated agriculture and groundwater containing different types of salts. Drainage that removes salt from irrigated lands is necessary for large-scale irrigation to be sustainable (Oster and Grattan, 2002; Wichelns and Oster, 2006). In irrigated areas, increases in cropping intensity, excessive use of fertilizers and pesticides, and inappropriate irrigation methods contribute to increased salt loads in drainage water (Oster and Wichelns, 2003). Moreover, geological saline deposits often exist along the drainage water flow path. As drainage water flows through these deposits, the salt loads in the resulting drainage water can considerably exceed those projected to occur from irrigation alone (Van Schilfgaarde, 1994). The groundwater resources in most arid and semiarid areas under irrigation are saline and in certain cases farmers have high dependence on groundwater for irrigation. The management and productivity enhancement options vary with the level and type of salts in the water resources used for irrigation but policy instruments and economic incentives are often lacking for promoting the sustainable management of these resources.

Salt-affected soils are generally categorized into saline, sodic (~alkali) and saline-sodic (~saline-alkali) soils. Saline soils contain excess soluble salts that adversely affect the growth of most crop plants. Sodic soils are characterized by elevated levels of sodium ions and exhibit structural problems as a result of certain physical processes (slaking, swelling and dispersion of clay) and specific conditions (surface crusting and hard-setting). Having overlapping properties, saline-sodic soils are characterized by both elevated levels of soluble salts and sodium ions. Recent evidence from different parts of the world has helped in characterizing another type of salt-affected soil, i.e. soil that is affected by magnesium (Vyshpolsky et al., 2008). With high levels of magnesium, when plowed, these soils form large clods that impede water flow resulting in poor water distribution and plant growth. As high sodium and magnesium content contributes to soil degradation, magnesium-affected soils share several common features with sodic soils.

The restoration of salt-affected soils is governed by the given context. With saline soils, the cost of restoration usually increases with the degree of salinization. For example, a moderately saline soil would require less investment to bring it back to a productive state than a highly saline soil under similar conditions, although both soils fall under the ‘saline soil’ category (Qadir et al., 2014). Similarly, the quantity and related cost of a calcium source, such as gypsum, increases with the level of sodium in sodic soils or magnesium in magnesium-affected soils (Garcia-Ocampo, 2003; Vyshpolsky et al., 2008). In addition, if there is a compacted layer in the subsoil – which needs to be broken to leach the salts from the root zone – the cost of land restoration is affected. Other factors affecting the cost of land restoration include the quality and quantity of water available for leaching; the quality and depth of groundwater; the crops to be grown during and after soil amelioration and their market value; the topographic features of the land; and the climatic conditions, as soils under a hot and arid climate need more water to reach a specific level of remediation than those in a cold and humid climate, all other factors remaining constant (Qadir et al., 2014).

POTENTIAL BENEFITS FROM SALINE WATER AND SALT-AFFECTED LAND

By practicing saline water recycling and reuse until it becomes inoperable for any economic activity and restoring salt-affected irrigated areas back to production, a significant contribution to national, regional and global food security could be achieved without expanding the production area and obviating the associated challenges that this brings. Otherwise, land retirement or more commonly abandonment because of salinization, negates the investments made to deliver water to farms via waterway networks as well as those for supporting local agro industry, institutions and infrastructure. Therefore it makes sound economic sense to utilize each drop of saline water, reverse salt-induced land degradation and ameliorate salt-affected lands, thereby increasing agricultural productivity and supporting community livelihoods. This would also help to keep communities on their land instead of generating environmental refugees who migrate to nearby urban settings for subsistence non-farm activities to support their livelihoods while their land continues to degrade and their skillsets are underutilized.

In addition to the economic benefits from saline water recycling and reuse and reversing salt-induced land degradation, there are notable environmental benefits such as mitigating climate change impacts (Wicke et al., 2011). For example, during salt-induced degradation, salt-affected lands lose a significant fraction of their original carbon pool (Ivits et al., 2013) and biomass productivity potential (John et al., 2005). The magnitude of the loss may range between 10 and 30 t carbon/ha depending on the original size of the carbon pool and the severity of land degradation (Lal, 2001). The soil carbon pool, which consists of both organic and inorganic carbon, is important with respect to productivity and the environmental functions soil performs; it also plays an important role in the global carbon cycle. It is possible to enhance soil carbon sequestration by restoring salt-affected lands. Studies undertaken along these lines have demonstrated that reversing salt-induced land degradation and cultivation of appropriate salt-tolerant crops, shrubs and trees on such soils have the potential to mitigate greenhouse gas emission effects by increasing the amount of carbon sequestered in the soil through the production of biomass (Lal, 2002; Kaur et al., 2002; Qadir et al., 2006). The types of crops to be grown in salt-affected environments depend on the ambient levels of salts in irrigation water and salt-affected lands, i.e. the level of irrigation water and soil salinity. Guidelines are available in this regard (Maas and Grattan, 1999) yet cropping decisions are rarely driven by the salt levels and carrying capacity of the systems.

Besides carbon sequestration, there are additional benefits stemming from ecosystem services resulting from the restoration of degraded lands such as recreation and aesthetic values; also, reduction in environmental degradation through improvements in soil health and structure, surface water and groundwater quality, and air quality. Valuation of such ecosystem services is expected to result in favorable environmental and economic benefits, although functional markets for many of the ecosystem service benefits are currently embryonic or non-existent (Qadir et al., 2014).

Relatively few studies have been undertaken on the economics of saline water recycling and reuse and reversing salt-induced land degradation. Examples included in this report are:

- Concentration of salts in a sequential manner for effective management of saline drainage water combined with income-generating crop, aquaculture, potable water and industrial salt production;
- Production of decentralized and renewable energy by using microhydro-turbines along the natural flow of the saline water in drainage water collector networks;
- Profitable horticulture that harnesses solar energy for seawater desalination to produce freshwater for greenhouse irrigation;
- Large-scale drainage water reuse in the Nile Delta in Egypt with mixed benefits, challenges and opportunities;
- Use of phosphogypsum to mitigate magnesium effects in magnesium-affected lands and to enhance crop productivity;
- Phytoremediation of highly saline abandoned lands by growing salt-tolerant shrubs followed by field crops;
- Plantation of multipurpose salt-tolerant tree species on salt-affected wastelands for biomass and bioenergy production; and
- Large-scale amelioration of sodic soils via gypsum application supported by a number of coordinated actions involving relevant stakeholders.

Each case study section addresses the nature of the specific problem, the approach used in implementing the strategy for transforming the problem into opportunity, and the key considerations related to the challenges in implementing the strategy.

Sequential Biological Concentration of Saline Waters Combined with Crop, Aquaculture, Potable Water and Industrial Salt Production

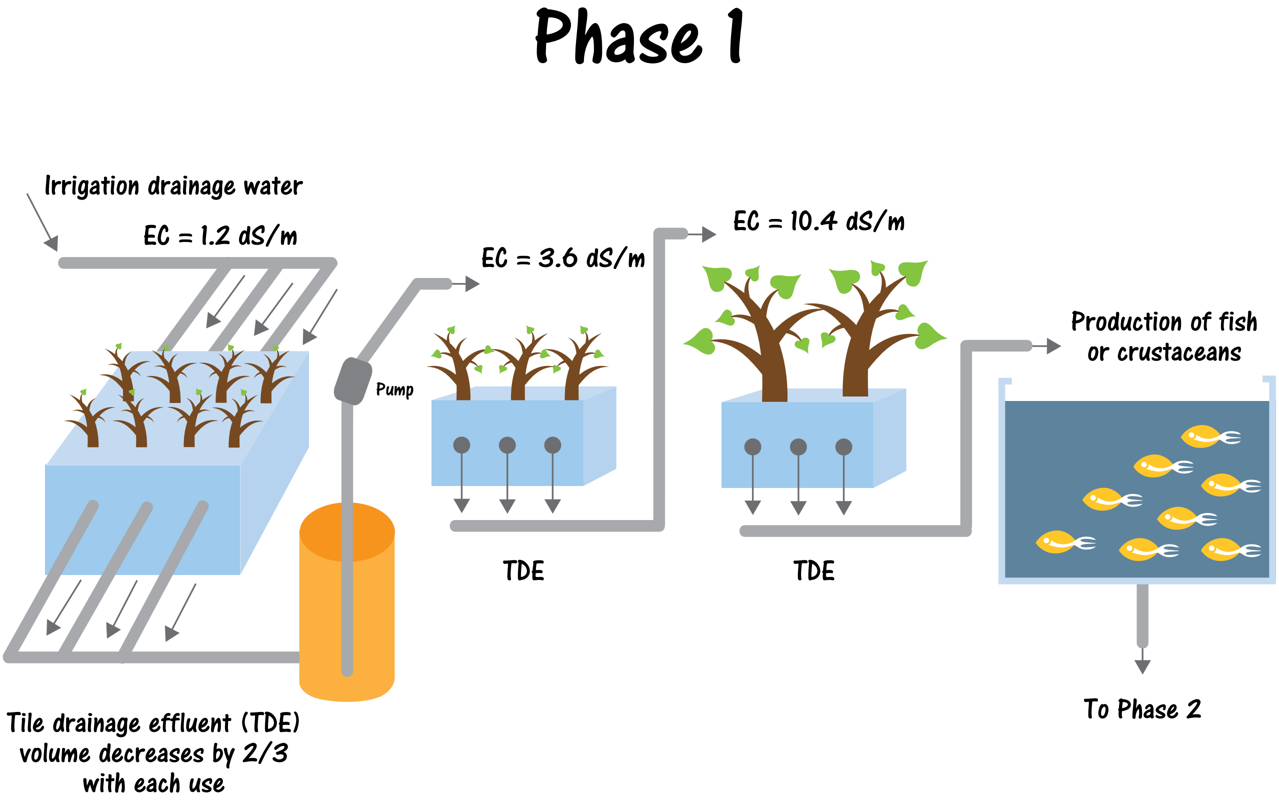
Rationale and Approach

Irrigated areas – including salt-affected irrigated land using subsurface or open drainage schemes – generate drainage water that is of lower quality than the applied irrigation water. This is an inevitable consequence of irrigation at the system level. After irrigation, the water added to the soil is used by the crop or evaporates directly from the moist soil. The salt, however, is left behind in the topsoil, i.e. the root zone. To prevent excessive accumulation of salt in the root zone, water exceeding the crop water requirement must be applied via irrigation for salt leaching. Salt leaching may be achieved either by applying sufficient water at each irrigation event to meet the leaching requirement or by applying, less frequently, leaching irrigation sufficient to remove the salts accumulated from previous irrigations. During the salt-leaching process, native salts in the irrigated soil move through the soil profile, thus adding salt to drainage water or groundwater (Lin and Garcia, 2012). Therefore large volumes of saline water must be appropriately managed to prevent production losses and deleterious off-site environmental impacts in the long term (Ali et al., 2001; Tanji et al., 2002). The challenge for most irrigation systems is minimization and the disposal of salt-laden drainage water. Although these waters are often viewed as a 'problem', they could represent an 'opportunity' leading to economic and environmental gains.

Two generic options for local management of saline drainage waters are (1) reuse for irrigation and (2) disposal to evaporation basins for regional storage (Su et al., 2005). In the first case, the reuse of drainage water to directly irrigate downstream crops by traditional irrigation methods is less sustainable than the original irrigation water as the drainage water contains higher concentrations of salts than the applied irrigation water. In the latter case, there is the missed opportunity to productively utilize saline drainage waters and such an approach should only be considered where the productive use of these waters is deemed to be economically unsuitable.

Sequential Biological Concentration (SBC) of saline drainage streams creates a number of financial opportunities, while concentrating the waste stream into a manageable volume (Blackwell et al., 2005; Khan et al., 2007). Phase 1 of SBC involves serial irrigation of crops based on their salt tolerance. A key element of Phase 1 is maintaining the generation of a relatively high leaching fraction (i.e. one-third of the water applied) to manage root zone salinity and crop growth at the desired level. Several crops to be used in SBC systems have the potential to produce commercial yields when irrigated with waters of increasing levels of salts. The salt concentration process aims to significantly reduce the volume of drainage water and therefore the size of the evaporation basin needed for final disposal. The number of stages used in the design of Phase 1 depends on soil and irrigation water salinity as well as the salt tolerance of the plants used in the system. Usually water is used three times and each stage reduces the volume of water through transpiration and evaporation by around two-thirds while concentrating the salt content until it reaches a level where no crops can grow (Toohey et al., 2003). With the salt concentrated in water being close to that of seawater levels, the water is pumped into a pond effectively representing an 'inland fish pond' in which the salinity levels are high enough to raise marine species in an aquaculture production system, i.e. crustaceans and pelagic fish can thrive when the salt concentration conforms to that of their natural habitats (Figure 1). When salinity of the concentrated water reaches a level that pelagic fish cannot tolerate, the water is moved to Phase 2 for further reuse.

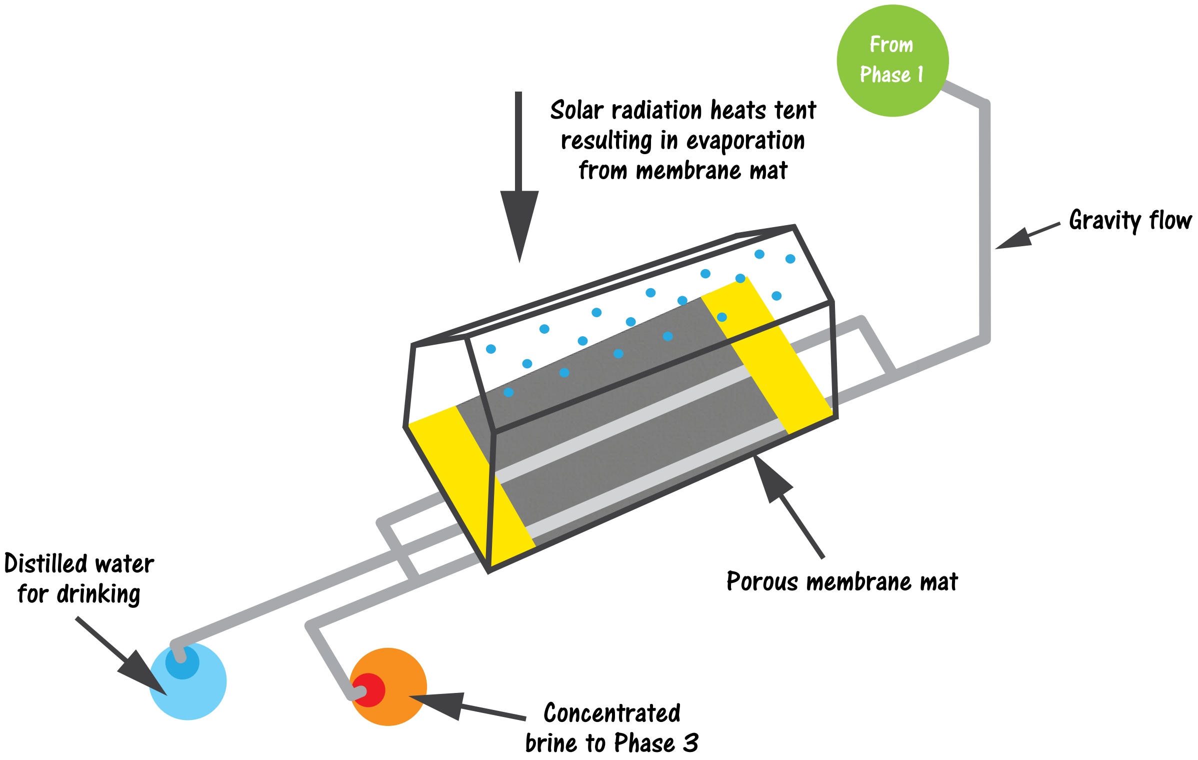
FIGURE 1. SEQUENTIAL BIOLOGICAL CONCENTRATION (SBC) PHASES AND POTENTIAL BUSINESS OPPORTUNITIES FROM SALINE DRAINAGE WATER MANAGEMENT (BASED ON TOOHEY ET AL., 2003; BLACKWELL ET AL., 2005; KHAN ET AL., 2007).



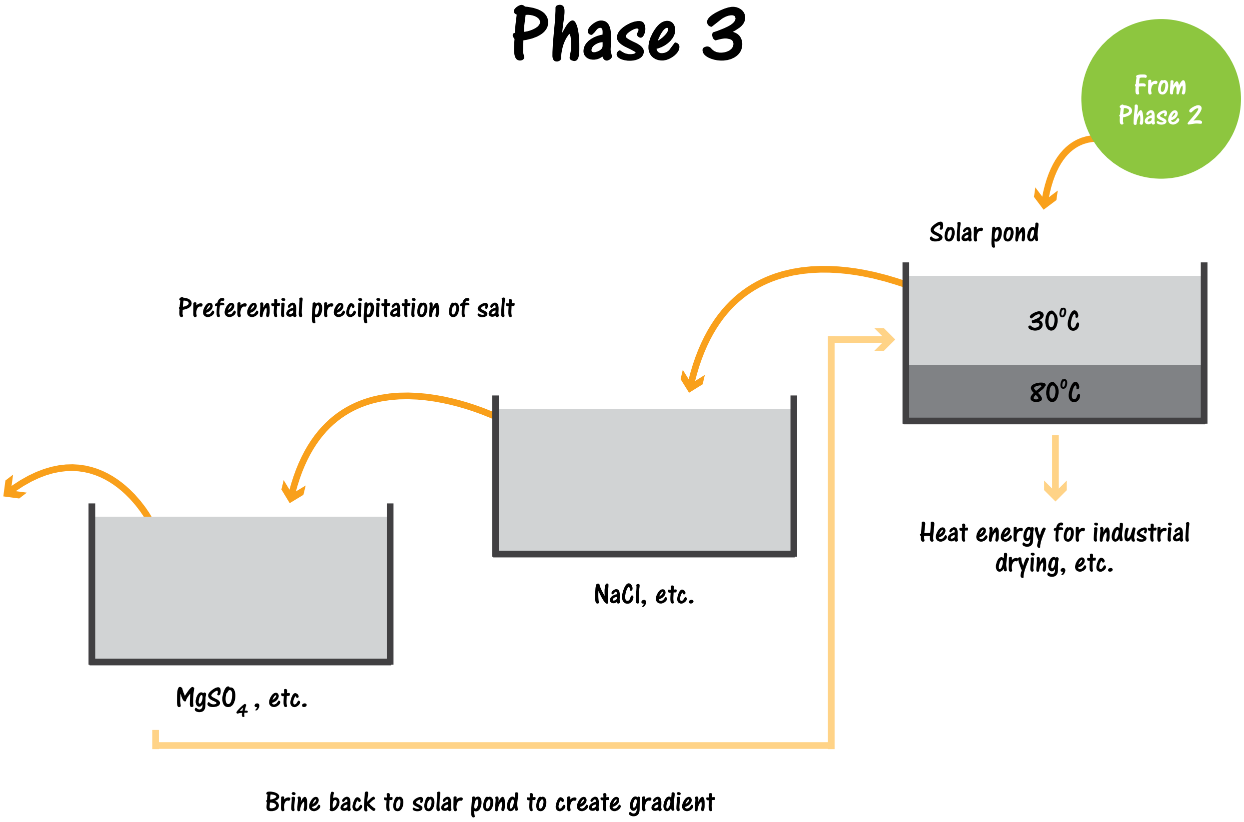
(Continued)

FIGURE 1. SEQUENTIAL BIOLOGICAL CONCENTRATION (SBC) PHASES AND POTENTIAL BUSINESS OPPORTUNITIES FROM SALINE DRAINAGE WATER MANAGEMENT (BASED ON TOOHEY ET AL., 2003; BLACKWELL ET AL., 2005; KHAN ET AL., 2007). (CONTINUED)

Phase 2



Phase 3



In Phase 2, through a system of perforated pipes (a technology developed by Shell in the separation of oil from water) and within an evaporation tent, the saline water is moved through the network of these pipes, allowing for the condensation of distilled water that can be used as potable water (Figure 1). The remaining component, concentrated brine, is moved to Phase 3 of the system.

In Phase 3, the salt is concentrated up to a level that can be viewed as hyposaline; because of its density the solution sinks to the bottom of a tank that captures solar energy resulting in the hyposaline solution reaching temperatures of 80ºC. The energy entrapped in the hyposaline solution may be sufficient to power the whole site (Toohey et al., 2003) and/or can be used in drying processes. Brine shrimp can be grown in the upper surface waters of these tanks, again adding economic value to the water. The final stage includes the preferential precipitation of constituent salts that make up the solutions congruent with how table salt (sodium chloride) is produced from seawater. These salts can be preferentially 'dropped-out' from the solution to produce industrial salts, such as magnesium sulfate and magnesium chloride (Figure 1).

Toohey et al. (2003) evaluated the financial viability of the SBC system in the Murrumbidgee Irrigation Area (MIA), Australia while using cost-benefit analysis, and then assessed the viability of the system by calculating the Net Present Value (NPV) and Internal Rate of Return (IRR) over a 30-year period and an assumed discount rate of 7%. They considered that the SBC for the MIA intercepts 10 million cubic meters (m^3) of winter drainage flow at an average salinity level of 1.2 dS/m whereas the SBC for the Yanco Main Southern Drain intercepts all the drainage flows (winter and summer) totaling 4.4 million m^3 and has an average salinity level of 0.8 dS/m. The results for the MIA showed that the SBC was financially viable on a minimum area of 100 ha of grape vines, but has the potential to generate high returns if a considerable area under the vines is part of a mixed cropping system. For the Yanco Main Southern Drain, the SBC was financially viable without grape production due to: (1) better quality of water diverted from the drain (i.e. 0.8 dS/m as compared to 1.2 dS/m resulting in less yield losses in each cropping stage); and (2) less storage required (reduced capital cost) as crop production can utilize summer drainage flows. These scenarios did not take into account any external benefits resulting from the SBC system. For example, in the case of the MIA, the agricultural and environmental benefits to Wah Wah Irrigation District of removing 6,300 tonnes of salt per year and the estimated annual value of agricultural benefits only amounted to AUD 340,000.

Although each of the individual phases of the SBC system are proven technologies, these phases have neither been put together in an entire package nor considered within the context of managing saline drainage waters within the irrigation sector through an entire value-adding chain. The SBC system is best suited to 'end of system' design and may not be well adapted to individual on-farm operation, particularly in developing countries where subsistence farmers are not in a position to spare land or to pay the full cost for the safe and productive management of drainage water they produce on farm. This offers opportunities for institutionalizing drainage water disposal through public and private sector investments where there will be a need to build institutions that will take drainage water away and add value to it in a manner similar to urban areas where a sewage management fee is charged. Such a system would facilitate bringing in expertise from a broad range of disciplines. For example, irrigation companies would be the most appropriate entity to own and control an SBC system while other private companies can provide finances for the business and marketing opportunities for the produce from SBC schemes; however, as it is a farming system, farmers' expertise needs to be used in its day-to-day operations.

In other developed-country regions such as San Joaquin Valley in California, research and practice have clearly demonstrated the technical feasibility of reducing the volume component of saline drainage water, thus opening up opportunities for solar processing and utilization of the salts (Toohey et al., 2003). In San Joaquin Valley, the demonstration of integrated on-farm drainage management has been implemented at the Red Rock Ranch – a highly salinized farm. Farm operation was divided into four salinity areas (zones). Relatively good-quality irrigation water was applied to major commercial crops grown in the non-saline zone, which represented 184 ha (73.4%) of the farm area. Saline drainage was sequentially reused to irrigate salt-tolerant commercial crops grown on 51 ha (20.3%) of the farm in the low-saline zone. Various salt-tolerant trees and grasses were grown in the moderate-saline zone (5 ha; 2.0%), and halophytes were grown in the high-saline zone (2 ha; 0.8%). About 85% of the drainage volume was productively reused in this process. Salts concentrated in the remaining 15% of drainage volume were collected in a solar evaporator for water evaporation and salt crystallization. The solar evaporator was located on 0.75 ha (0.3%) of the farm area while irrigation infrastructure occupied 3.2% of the area (Cervinka et al., 1999). Saline drainage was also used in a solar pond for heat/power generation, or processed to separate sodium sulfate, sodium chloride and other pure salts. Economic assessment (Toohey et al., 2003) revealed that the benefits from the investment of USD 1,497/ha were increase in land value by USD 4,090/ha and annual crop net return by USD 447-934/ha. The farm operations remained in place effectively for several years. However, drainage water reuse stopped by 2009, in part due to the drought in 2008, with less volume of good-quality water available for the non-saline zone, which impacted the volume of drainage water required in subsequent phases. This also led to economic problems with the farm operations resulting in dissolution of the farm operation and leasing out the land to a neighbor (Sharon Benes, personal communication). This situation warrants the development of mechanisms in the planning phase for alternate supply of water and other resources when their availability is restricted, in addition to availability of supportive funds to continue farm operations when there are farm input constraints. This would need a well-coordinated business plan.

Successful drainage water reuse in California is exemplified in southern Kern County where a range of crops (bell peppers, carrots, asparagus, tomatoes and melons) has been grown with freshwater; drainage water from these fields is collected and used to irrigate halophytes such as salt grass and iodine bushes. The final effluent goes to a solar evaporator. This system has also enhanced soil quality (Sharon Benes, personal communication). Another example is the San Joaquin River Improvement Project operated by Panoche Water District, north of Los Banos. The drainage water is collected from 40,000 ha of land and reused mostly to grow Jose Tall Wheatgrass on about 1,500 ha, alfalfa on nearly 400 ha and pistachio on 38 ha (Linneman et al., 2014). Implementation of the drainage water reuse component of the project has allowed continued farming of 40,000 ha of highly productive farmland. Through drainage reuse, the farmers have been able to achieve water quality objectives set by the Central Valley Water Quality Control Board related to subsurface drainage discharges while also maintaining viable agricultural production in the area. The data from 2012 discharges show the true success story of the project: 94% reduction in selenium discharge; drainage volume down by 82%; boron and salt load down by 74% and 84%, respectively (Linneman et al., 2014).

Key Considerations for Implementation

Integrating agriculture and aquaculture systems based on the SBC system using saline drainage water sequentially has the potential for commercial, social and environmental gains. Amid food security concerns, it is important to assess the viability and practicality of developing the SBC system in managing saline drainage water through the establishment of fully functional pilot sites in developing countries. These sites should be considered and evaluated as potential business opportunities in major river basins where large volumes of saline drainage waters are generated and their disposal options are limited. These sites will also help in fine-tuning the procedures and techniques under climate and resource variability. For instance, droughts and scarcity of freshwater leading to inequity in water distribution and reduction in drainage flows may pose sustainability challenges for the implementation of SBC systems.

The scale of operation to make the SBC system a profitable and sustainable venture is crucial in decision making as the system is considered to be financially viable only on a minimum area of 100 ha. Where landholdings are large in developing countries, individual farmers can allocate small portions of their land for SBC operations while maintaining the productivity of the remaining land. Community-based implementation of SBC may work for medium-scale farmers through land pooling for SBC and benefit sharing. The major challenge is in areas where landholdings are usually small (less than 5 ha). In such situations, the role of different stakeholders is important to lead community-based action. The major stakeholders are policy-makers, government institutions, farmers, farmer/water-user associations, the private sector and local and regional markets dealing with forage, feed and fish, and possibly salt and timber where available.

Saline Drainage Water Collector Networks for Energy Production

Rationale and Approach

Energy is a key driver of development and therefore economic growth, which improves wellbeing through local economic development and poverty reduction. Hydropower has a strategic advantage over wind and solar power in terms of reliability and storage. By 2035, hydropower is expected to provide half of global energy generation based on renewable forms, wind almost one-quarter and solar 7.5% (IEA, 2012). Despite the importance of hydropower, many energy-deficient countries lag behind substantially in achieving potential hydropower capacity. For example, only 30% of the technically exploitable hydropower capacity is capitalized in Uzbekistan (Eshchanov, 2006). This refers mainly to the potential for large dams, and does not focus on small, decentralized, off-grid schemes. It is important to note that since 1996, Uzbekistan has been a net electricity importer and power generation in the country has been decreasing since its independence. In rural areas, where 62% of the country's population resides, the supply of electricity is not stable (ADB, 2003).

Despite the variable levels of energy dependence, almost all farming operations require energy such as irrigation operations that need it for lifting water, plowing, chiseling and so forth. Notwithstanding this continuous demand, many irrigated areas, particularly in developing countries, suffer from energy supply shortages. The collector networks of agricultural drainage water however can be used for operating microturbines in order to produce decentralized and environmentally-clean energy using the natural flow of the drainage water. This could narrow the gap between energy demand and supply, which is of particular importance in rural areas, or in areas where energy production has traditionally been dependent on large hydropower dams and where little attention has been paid to small-scale energy production systems. For example, in Central Asia it is estimated that along the irrigation system in the Aral Sea Basin, there are at least 10,000 sites that could be used for microhydro-turbine schemes and hence for renewable energy production (Qadir et al., 2010). This is particularly important if these sites are located in remote areas or belong to poor communities. There are also other river basins where saline drainage water networks are present and a significant proportion of salt-affected soils occur on land inhabited by smallholder farmers.

The hydropower potential from natural water flows in Uzbekistan is estimated at about 20,000 MW (ADB, 2003). About 30% of this could come from small hydropower sources such as microhydro-turbines, especially off-grid power generation from (1) the extensive irrigation network that extends over 196,000 kilometers (km) in the Aral Sea Basin and (2) the drainage water collector network that extends over 110,000 km. Although microturbines may not be efficient at the tail-end of the system where the slope is flat, there are many locations in the uplands where sufficient slope is available (Qadir et al., 2010). In addition, many regulated gated points in the irrigation network as well as small water streams and rivulets can provide sufficient hydraulic pressure heads of approximately 0.3-1.0 m that can be used for operating microhydro-turbines. These turbines in rural areas represent an environmentally-clean source of energy for pumping water, lighting and heating, and additionally running flour mills, among other purposes. In addition to slope and flow of water, the efficiency of these turbines depends on blade design as well as turbine size and speed. Different types of microturbines with different features are available in the market. Examples include the Pelton, Francis and Kaplan products.

Small, decentralized, off-grid schemes can serve tens or hundreds of households. These systems are present in several countries that include China, India, Nepal, Vietnam and Sri Lanka (REN21, 2007) and can produce up to 100 kW of electricity. The energy is produced at a low cost; for example, the costs of USD 0.06/kWh (Kyrgyz Republic) and USD 0.04/kWh (China) represent one-tenth of the costs of grid generation (ADB, 2003). The international community is also paying attention to the potential of off-grid energy production. While documenting the World Energy Outlook, the International Energy Agency emphasized the need for the energy sector to exploit nonfreshwater sources such as saline water for water reuse technologies, including hydropower potential (IEA, 2012).

Key Considerations for Implementation

Small-scale decentralized energy production can be achieved in developing countries where large volumes of saline drainage water are generated and where there is an energy crisis, particularly in rural areas. However, it is important to establish fully functional pilot sites to assess the economic viability and practicality of saline drainage water networks to produce such environmentally-clean energy. Provision and maintenance of a functional drainage system are prerequisite to ensure adequate flow of drainage water in drainage water collector networks to generate energy.

While the technology and different types of microturbines are available to produce off-grid energy, the expected challenges are: (1) limited technical expertise in initiating and demonstrating decentralized energy generation systems and backstopping their operation and maintenance issues; (2) lack of policies for promoting and facilitating energy generation through supportive mechanisms such as tax relaxation on importing or manufacturing microturbines and their parts, integrating decentralized energy generation into national energy strategy and providing soft loans to communities to purchase and install microturbines for clean and renewable energy production; (3) negligible operational knowledge of the equipment by communities adjacent to the drainage networks and immediate beneficiaries of the energy, necessitating training of these communities; and (4) absence of mechanisms to distribute the energy among communities, beyond the drainage network communities, as well as associated tariff and revenue collection systems. While addressing these challenges, initial financial support and institutional arrangements from governments can play an important role in initiating and managing pilot studies and subsequent implementation using saline drainage water collector networks for decentralized energy production.

Profitable Horticulture Based on Solar Energy for Seawater Desalination to Produce Freshwater for Greenhouse Irrigation

Rationale and Approach

In recent years, the private sector has been increasingly emerging as a key player in making productive and profitable use of saline water through sustainable horticulture production in dry areas. This has been accomplished by growing high-value crops via abundant renewable resources – sunlight and seawater or highly saline groundwater. For example, the Sundrop Farms System™ based in South Australia harnesses solar energy for desalination of seawater to produce freshwater for greenhouse irrigation and to produce electricity for heating and cooling greenhouses (Sundrop Farms, 2014). The seawater-drenched greenhouse ventilation system cleans and sterilizes the air, making it possible to grow crops without chemical pesticides. The system operates at optimum efficiency and profitability when located in arid regions with plenty of sunshine, close to the sea or a saline water resource and in close proximity to consumer end-markets. The availability of flat land for the system is essential for more cost-effective greenhouse construction and management. The cultivation of crops such as cucumber, capsicum and tomato has shown profitable returns since the farm started operation in 2010. The greenhouse-based farm follows standard food safety measures and is certified in accordance with the Hazard

Analysis Critical Control Points (HACCP) protocol, Australia's food safety certification system.

The major benefits from the Sundrop Farms System™ based on cucumber, capsicum and tomatoes cultivation as summarized by the company are: (1) freshwater production from seawater; (2) reduction in fossil fuel requirement due to the use of solar energy for desalination of seawater; (3) reduction in the use of pesticides due to greenhouse ventilation that cleans and sterilizes the air; (4) less land area needed because of high productivity – 15 to 30 times more produce per unit area than conventional field production; (5) valuable salt and mineral production (for other users such as the livestock industry) from sustainable desalination of seawater or highly saline groundwater with solar energy; (6) lower transportation cost due to production proximity to end-consumers in an era when modern horticultural production often stretches fresh food supply chains across the world; (7) provision of more jobs per unit area – five to seven people per hectare of greenhouse on a long-term green employment basis; (8) lower operating costs that increase profit margins and protect consumers from price swings; and (9) healthier and better-tasting produce (Sundrop Farms, 2014).

In August 2013, the Clean Energy Finance Corporation (CEFC) and Sundrop Farms undertook an arrangement for the CEFC to co-finance a major greenhouse development project near Port Augusta, South Australia, which will use solar-thermal technology to desalinate seawater to provide irrigation, and to heat and cool greenhouses. This system will be based on a 20-ha greenhouse facility, which will produce over 15,000 tonnes of tomatoes a year for metropolitan markets across Australia.

Key Considerations for Implementation

This potential business opportunity creates environmentally-friendly water and energy. While the farm operations have been underway since 2010 with reported profits, economic details in terms of the costs and benefits are not available yet. These data are important to make evidence-based decisions. Availability of material and supplies for establishing a greenhouse and its associated irrigation system is important, particularly in developing countries.

Freshwater scarcity and very high salinity in rivers are key drivers for such business innovations. Supportive regulations could also be a critical factor for the success – in Australia, quarantine regulations restrict vegetable imports to protect public health and unique flora and fauna, while state and national green-energy programs on clean and renewable energy promote investments in such innovations. There is a need to introduce incentives for environmentally-friendly greenhouse operations such as tax relaxation and provision of rebates, among other concessions.

Large-scale Drainage Water Reuse in the Nile Delta: Mixed Benefits, Challenges and Opportunities

Rationale and Approach

Irrigation deliveries in the Nile Delta in Egypt contain a mixture of freshwater and saline drainage water, as both the government and individual farmers use drainage water to extend the available irrigation supply. The government intended to practice drainage water reuse since 1928, when it constructed the first of many pumping stations that lift drainage water from drains and place it into delivery canals (Abdel Ghaffar and Shaban, 2014). However, massive reinjection of drainage water from main drains into main canals and later from secondary drains to secondary canals started some 30 years ago.

With population growth and increasing water scarcity in the Nile Delta, the reuse of drainage water is on the rise (Omar, 2011); this amounted to 6.86 billion m^3 in 2008 and is expected to reach 8.70 billion m^3 in 2017 while keeping the targeted salt-level limit below 2,000 mg/L (3.1 dS/m).

Saline drainage water in the Nile Delta is transported by an extensive drainage network; 89 main drains flow directly into the Nile River. Except for some pumping stations in the Northern Delta, the drainage system is largely based on gravity flow. There is an extensive monitoring network consisting of 232 sites for assessment of the quantity and quality of drainage water in the main and branch drains. The Supreme Council for Protection of the River Nile and Waterways from Pollution, created in 2009, stipulates regulatory measures via Decree No. 3318 of the Prime Minister of Egypt. However, the informal current use of drainage water is estimated at 2.7 billion m^3 (Omar, 2011), which takes place in areas with canal water shortage, mainly at canal tails without permission from the Egyptian Ministry of Water Resources and Irrigation. The ministry is also undertaking major drainage water reuse expansion projects to divert considerable amounts of drainage water to newly reclaimed areas after blending with freshwater. There are two major expansion projects: (1) the El-Salam Canal Project, which according to planning figures will provide 2 billion m^3 of drainage water from the Bahr Hadous and Lower Serw drains, mixed with 2 billion m^3 of freshwater from the Nile River (Damietta Branch), yielding a water supply of 4 billion m^3 to irrigate 92,500 ha west of the Suez Canal and 168,000 ha in Sinai (of which less than one third is currently under cultivation); and (2) the Umoum Project, which is based on reuse of 1 billion m^3 of drainage water (Abu Humus, Shershra and Truga catchments) to irrigate 202,000 ha in Nubaria (Omar, 2011), partly stalled because of low water quality.

The Egyptian Government attempts to optimize drainage water use in the Nile Delta by managing the pumping and blending of drainage water at a series of large-scale pumping stations, in accordance with engineering and agronomic criteria (Abdel-Dayem et al., 2007). However, the unofficial use of drainage water by thousands of individual farmers complicates the aggregate effort to manage salt balance in the delta (Wichelns and Qadir, 2015). In addition, the disposal of untreated or inadequately treated wastewater into drainage canals prevails due to limited capacity for wastewater treatment in several areas with large-scale urbanization and industrialization (Abdel Ghaffar and Shaban, 2014). These practices have serious implications leading to water quality deterioration and land degradation.

The farmers generally are aware of the near- and long-term implications of continued irrigation with saline drainage water, yet they follow a potential business opportunity to place the near-term gains of crop income above the possible crop-yield losses over the long run due to salt accumulation in their soils (Wichelns and Qadir, 2015). Although laws and decrees have been issued, including guidelines for mixing drainage water with freshwater, regulations for sewage and industrial effluents, wastewater reuse, cropping patterns and health protection measures, as well as standards' specifications, the major problem lies in weak regulatory compliance and enforcement of the legislation.

Key Considerations for Implementation

Although there are notable benefits for the communities and government from drainage water reuse in Egypt, the current practices that circumvent guidelines and legislation may impact long-term sustainability of the Nile Delta for agricultural production systems. There is a need for comprehensive assessment for monetizing the benefits from the reuse of agricultural drainage water and costs related to potential environmental and health problems. This assessment would help in triggering policy-level decision-making to ensure benefits for the communities while minimizing environmental and health implications. Such an assessment and scenario development could be used to evaluate drainage water reuse practices and policies in other river basins elsewhere in arid and semiarid areas.

Productivity Enhancement of Magnesium-affected Soils with Phosphogypsum

Rationale and Approach

Excess levels of magnesium in soils, in combination with sodium or alone, result in soil degradation because of the specific effects of magnesium on the soil's physical properties (Qadir and Schubert, 2002; Karimov et al., 2009). Magnesium-affected soils contain an exchangeable magnesium percentage (EMP) in the range of 25 to 45% (Garcia-Ocampo, 2003), and in some cases, this is as high as 60% (Vyshpolsky et al., 2008).

There are examples from irrigation schemes worldwide where excess levels of magnesium on the soil's cation exchange complex have resulted in soil degradation and formation of magnesium-affected soils (Garcia-Ocampo, 2003; Karimov et al., 2009). For example in the Kazakhstan part of the Aral Sea Basin in Central Asia, more than 140,000 ha have these degraded soils (Vyshpolsky et al., 2008), i.e. more than 30% of the irrigated area (Vyshpolsky et al., 2010). Another example of magnesium-affected soils comes from South America where 117,000 ha are affected by high levels of magnesium in the Cauca River Valley in Colombia. The EMP levels range from 25 to 30% (Garcia-Ocampo, 2003). Soil data from some parts of Australia reveal considerably high levels of magnesium, although these soils are not yet formally classified as magnesium-affected soils.

Magnesium-affected soils tend to increase surface sealing and erosion during rainfall events (Dontsova and Norton, 2002). With low infiltration rate and hydraulic conductivity, these soils form large dense clods during the post-irrigation drying phase, which impact the water flow rate. The consequence of using magnesium-affected soils for agricultural production without suitable management practices has been a gradual decline in crop productivity and yield (Vyshpolsky et al., 2008; Karimov et al., 2009).

The productivity of magnesium-affected soils can be enhanced by increasing calcium at the soil's cation exchange sites to mitigate the effects of excessive exchangeable magnesium (Vyshpolsky et al., 2008). This can be accomplished by applying calcium to the soil, the amount based on the extent of exchangeable magnesium to be replaced. This amelioration strategy is similar to sodic soils where calcium supply mitigates the deleterious effects of sodium (Oster, 1982). While different sources of calcium have been used as a soil amendment in research and practice, gypsum ($CaSO_4 \bullet 2H_2O$) is the most commonly-used amendment because of its low cost. Phosphogypsum is another source of calcium mainly composed of gypsum. Its cost is lower than gypsum but its availability is site specific as it is the main byproduct in the production of phosphate fertilizer from phosphate rock. Application of phosphogypsum to soil offers additional value to farmers as it also supplies appreciable quantities of phosphorus to the soil (Delgado et al., 2002).

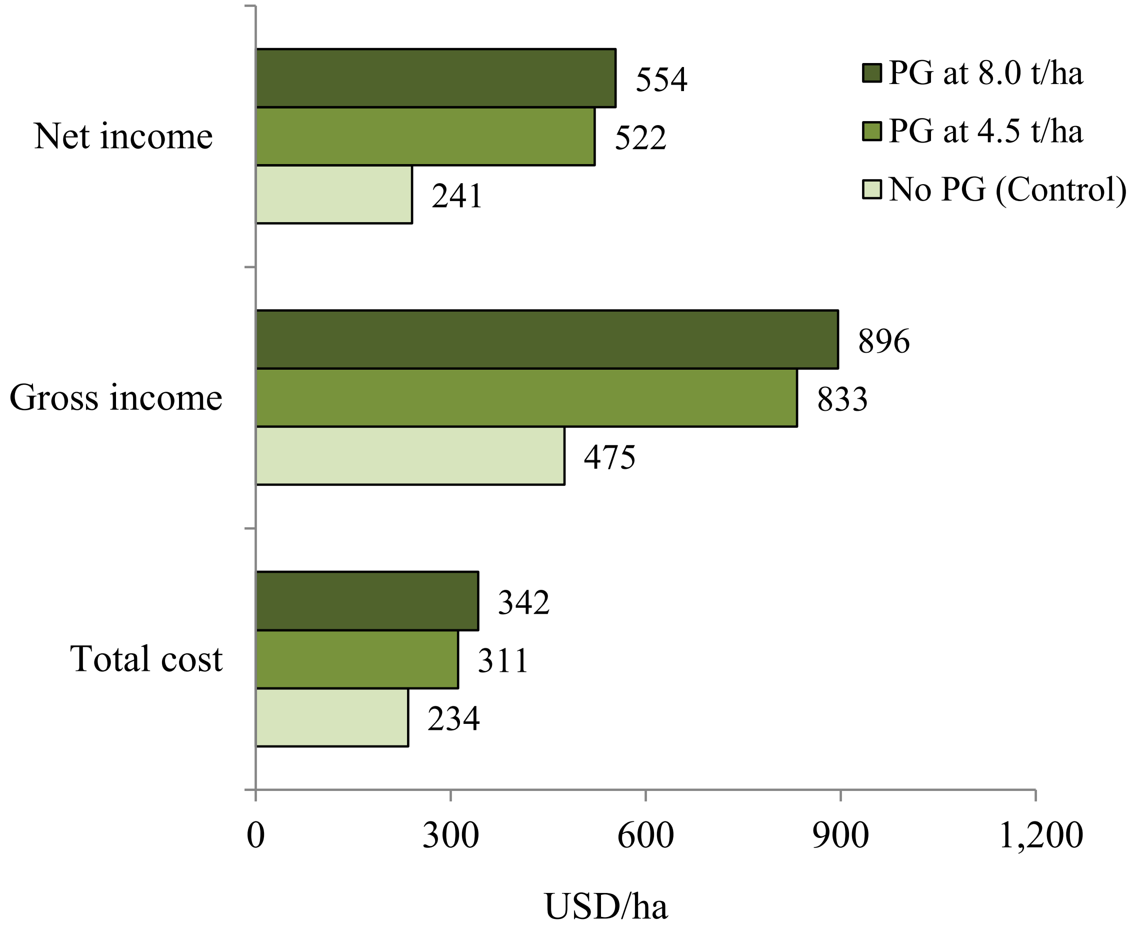
In a participatory study involving farmers, Vyshpolsky et al. (2008) used phosphogypsum to ameliorate magnesium-affected soils in southern Kazakhstan. The study consisted of three treatments with four replications: (1) control (no phosphogypsum application), (2) phosphogypsum application at 4.5 t/ha and (3) phosphogypsum application at 8.0 t/ha. The phosphogypsum application increased calcium concentration in the soil, which triggered the replacement of excess magnesium from the soil's cation exchange sites, causing significant decrease in EMP over the prestudy EMP levels. The four-year average cotton yields were 2.6 t/ha with soil application of 8 t phosphogypsum/ha, 2.4 t/ha with application of 4.5 t phosphogypsum/ha and 1.4 t/ha in the control.

An economic study of the applied treatments was undertaken based on: (1) purchase, transportation and field application costs of phosphogypsum for phosphogypsum treatments only during the first year of the study as no amendment was applied in subsequent years; (2) farm operations consisting of plowing, furrowing, harrowing, chiseling, purchasing cotton seed, sowing, weeding, harvesting and transportation of the harvest material; (3) fertilizer purchase and application; and (4) irrigation water provision. The gross income was calculated from the cotton yield and market price of cotton in the region in the respective year (Vyshpolsky et al., 2008). The net income from phosphogypsum application at 4.5 t/ha (USD 522/ha) and 8.0 t/ha (USD 554/ha) was double that of the control (USD 241/ha). For phosphogypsum treatments, additional economic gains (USD 32/ha) from the higher application rate of phosphogypsum (8 t/ha) were marginal; suggesting that the lower rate of phosphogypsum was optimal (Figure 2).

Since phosphogypsum was applied only once at the beginning, EMP levels tended to increase four years after its application as all the calcium from the amendment was gradually utilized in the amelioration process. This trend suggested the need for reapplication of phosphogypsum to such soils after every four to five years to sustain higher levels of cotton production.

Another field study was undertaken on a similar type of soil to find the appropriate combinations of the rates and timings of phosphogypsum application to mitigate the effects of high levels of magnesium (Vyshpolsky et al., 2010). There were five treatments: (1) control with no phosphogypsum application; (2) soil application of phosphogypsum in January before snowfall at the rate of 3.3 t/ha; (3) soil application of phosphogypsum in January before snowfall at the rate of 8.0 t/ha; (4) soil application of phosphogypsum in April after snowmelt at the rate of 3.3 t/

FIGURE 2. AVERAGE OF FOUR-YEAR DATA: TOTAL COST, GROSS INCOME AND NET INCOME THAT REFLECT THE ECONOMICS OF CONTROL AND PHOSPHOGYPSUM TREATMENTS (BASED ON DATA FROM VYSHPOLSKY ET AL., 2008).



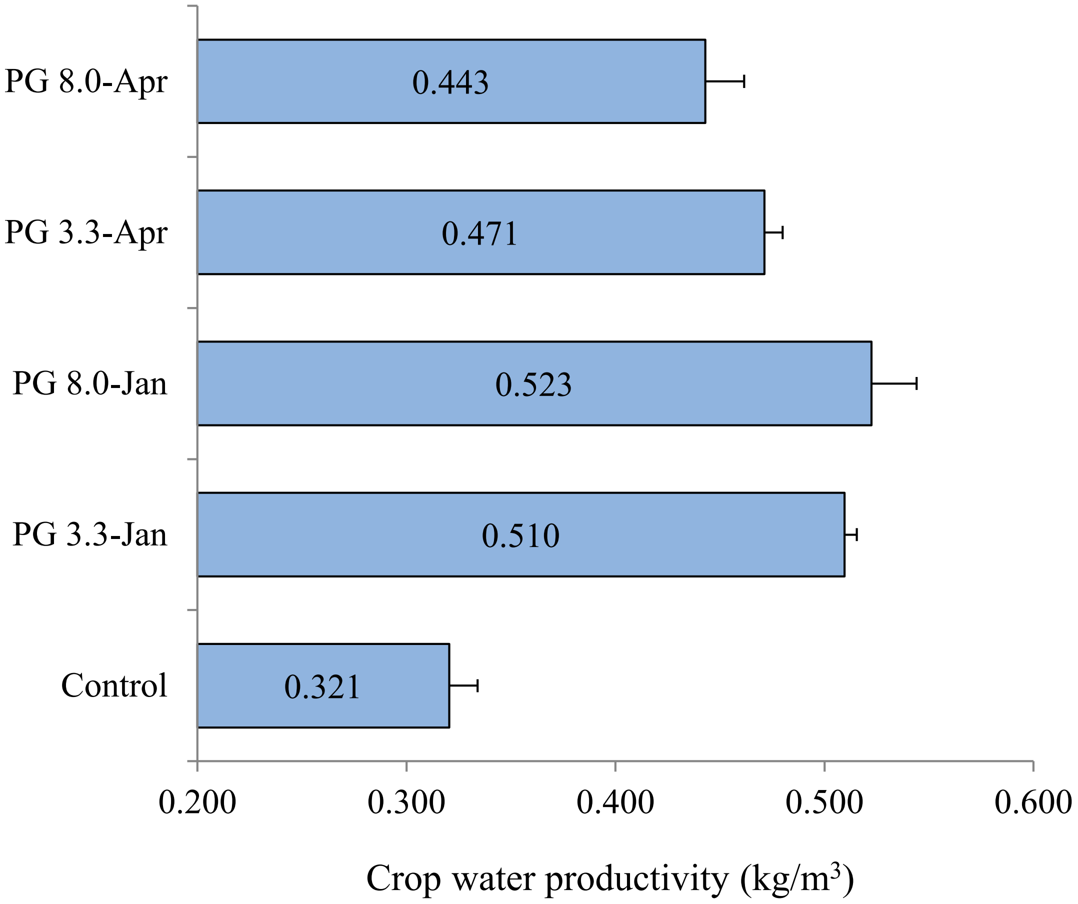
ha; and (5) soil application of phosphogypsum in April after snowmelt at the rate of 8.0 t/ha.

The phosphogypsum treatments performed better than the typical farming practice in terms of (1) improved soil quality through a reduction in EMP levels; (2) enhanced water movement into and through the soil vis-à-vis increased moisture storage in the soil for use by the plant roots; (3) increased cotton yield and water productivity; and (4) greater financial benefits (Vyshpolsky et al., 2010). In addition, surface runoff was significantly reduced in the phosphogypsum treatments, which improved the irrigation efficiency and effectively provided more moisture to the root zone through improved infiltration. This in turn increased crop water productivity in the phosphogypsum treatments. Two-year average water productivity in the control treatment was 0.32 kg/m^3 while it ranged from 0.44 to 0.52 kg/m^3 in the phosphogypsum treatments. Figure 3 shows water productivity of cotton as affected by different timings (before snowfall in January or after snowmelt in April) and rates of phosphogypsum application to a magnesium-affected soil. In terms of crop growth and yield, treatments receiving phosphogypsum produced 19 to 46% higher cotton yield than the control.

Based on the contribution of water from snowmelt for enhancing the dissolution of phosphogypsum in the soil, application of the amendment before snowfall improved soil properties to a greater extent compared to the application in spring after the snowmelt. The economic benefits in terms of marginal rate of return from phosphogypsum application at 3.3 t/ha were double those of treatments receiving the amendment at 8.0 t/ha, thereby suggesting that the lower rate was optimal. This rate of phosphogypsum application was based on the phosphogypsum requirement of the soil for 0.3 m depth.

With more farmers using phosphogypsum in the study area, they have a potential opportunity to become more independent from the local cotton-pricing system, which is largely influenced by private cotton trading companies. Most cotton growers in the area and cotton companies establish contracts on the 'future price' of cotton, which is usually predetermined by both parties. Farmers take loans from the companies to meet the costs of farm inputs and operations with an agreement to pay back the loan at crop harvest time. Such agreements benefit the companies because the cotton's 'future price' is always kept lower than the actual market price and farmers are

FIGURE 3. TWO-YEAR AVERAGE WATER PRODUCTIVITY AS AFFECTED BY DIFFERENT TIMINGS (BEFORE SNOWFALL IN JANUARY OR AFTER SNOWMELT IN APRIL) AND RATES OF PHOSPHOGYPSUM APPLICATION TO A MAGNESIUM-AFFECTED SOIL. THE ERROR BARS INDICATE THE STANDARD ERROR OF THE MEAN OF THREE REPLICATIONS (VYSHPOLSKY ET AL., 2010).



bound to sell the cotton to the contracted companies. Therefore, under a business-as-usual scenario where farmers continue growing cotton on magnesium-affected land, low cotton productivity from such degraded lands only helps them to pay off the loan they take at the beginning of the season, resulting in very small profits that barely offset their basic needs. Through phosphogypsum application that leads to higher productivity and profits, farmers have the opportunity to produce more cotton and become more independent by selling cotton in the open markets at more competitive prices. Currently, there are about 10 million tonnes of phosphogypsum available at the dumping sites of two phosphate fertilizer factories in Taraz and Shymkent. Considering phosphogypsum application at 5 t/ha, the amelioration of 140,000 ha of magnesium-affected soils in the area would need 0.7 million tonnes of the amendment.

Key Considerations for Implementation

While informal, this use of phosphogypsum can benefit farmers and other stakeholders across the cotton value chain in magnesium-affected and sodic soils. In both cases, the availability of a calcium-supplying soil amendment at an affordable cost is a prerequisite to turn farm operations into a business opportunity. The sources of calcium are gypsum and to a lesser extent phosphogypsum (as it is only available in areas where phosphate fertilizer is prepared from phosphate rock on an industrial scale). Another calcium source, lime ($CaCO_3$), is not suitable due to its negligible solubility at pH > 7, which is the usual pH range of these soils in irrigated areas. Its solubility increases tremendously in soils with low pH and it is used to ameliorate soil acidity.

As phosphogypsum is a waste product of the phosphate fertilizer industry, it is available to farmers at almost no/negligible cost – transportation remains the major cost. In this study, phosphogypsum was transported to the study area from a phosphate fertilizer factory about 300 km from the study site. The transportation cost was 86% of the total cost of phosphogypsum while procurement and application costs accounted for only 14% of the total cost. The transportation cost can be reduced by bulk movement of the amendment via freight train.

Phytoremediation of Highly Saline Abandoned Lands

Rationale and Approach

Waterlogging and salinization are major constraints affecting irrigated areas in cotton- and wheat-growing regions of Central Asia. The predominant reasons for their development are poor irrigation water management and inadequate drainage, rising groundwater tables and associated mobilization of primary salts within the soil profile. Approximately 600,000 ha of irrigated cropland in Central Asia became derelict during the 1990s due to waterlogging and salinization (Bucknall et al., 2003). It is estimated that approximately 20,000 ha of irrigated land in Uzbekistan are lost annually to salinity and are invariably abandoned, representing a significant loss of production and, more importantly, underutilization of irrigation infrastructure. The conventional approach to rehabilitating these salinized areas requires major technical expertise and investments that are beyond the means of national budgets as well as farmers' investment capacity in the Central Asian states.

In the Hungry Steppes in Uzbekistan, restoration of highly saline abandoned soils was undertaken using licorice (*Glycyrrhiza glabra* L., formerly *Liquiritae officinalis* Moench), a salt-tolerant perennial shrub species, as a phytoremediation crop (Kushiev et al., 2005). Licorice can grow to a height of 1.5 m and has a fusiform root system with numerous suckers that often grow more than 1-m deep and help in lowering shallow groundwater levels. The roots of licorice can be used for three main reasons: (1) sweet taste and may be chewed or eaten as a sweet, making it a useful component of candies; (2) reputed medicinal qualities; and (3) glycyrrhizinic acid can be extracted and used as a flavoring agent in food, tobacco, alcohol and cosmetics.

Licorice was grown on 13 ha that had been abandoned due to high levels of salts and shallow groundwater. An adjacent field of 10 ha was left as such during the study period of 1999 to 2003. The first crop of licorice fodder was harvested in 2001 and yielded dry matter at 3.6 t/ha with a protein content of 12%. By 2003, licorice fodder and root yields had progressively increased and reached 5.1 and 8.5 t/ha, respectively (Kushiev et al., 2005).

At the end of the 2003 growing season, the control and licorice fields were prepared for wheat-cotton rotations. Wheat yield was 2.42 t/ha after licorice cultivation and 0.87 t/ha from the control plots. Similarly, the soil remediation effects of licorice caused an increase in cotton yield from 0.31 to 1.89 t/ha (Figure 4). With average yields of wheat and cotton in the study area of 1.75 and 1.5 t/ha respectively, licorice demonstrated the potential to increase productivity and farm-level income from abandoned saline fields. This was attributed to a combination of lowering of the water table, enhanced leaching of salts associated with improved hydraulic conductivity and increase in soil organic carbon content (Kushiev et al., 2005). These biophysical indicators need to be supplemented by a cost-benefit analysis over the life time of the remediation projects. These data were not available for this study.

Key Considerations for Implementation

While phytoremediation through licorice cultivation seems promising, there are associated trade-offs. It is important to note that phytoremediation does not negate the role of a functional drainage system for improved management of salinity in the long term. Phytoremediation, however, offers an interim measure on the path to effective salinity management through salt and drainage management.

There are implications associated with the introduction of licorice in the remediation process as it is an invasive weedy species. Its extensive root system with the ability to develop suckers makes this species difficult to control without the use of herbicides that induce additional cost. Although licorice roots have multiple benefits, it is important to establish relevant markets and marketing opportunities for the communities opting for licorice production from salt-affected lands.

Plantation of Multipurpose Tree Species on Salt-affected Wastelands

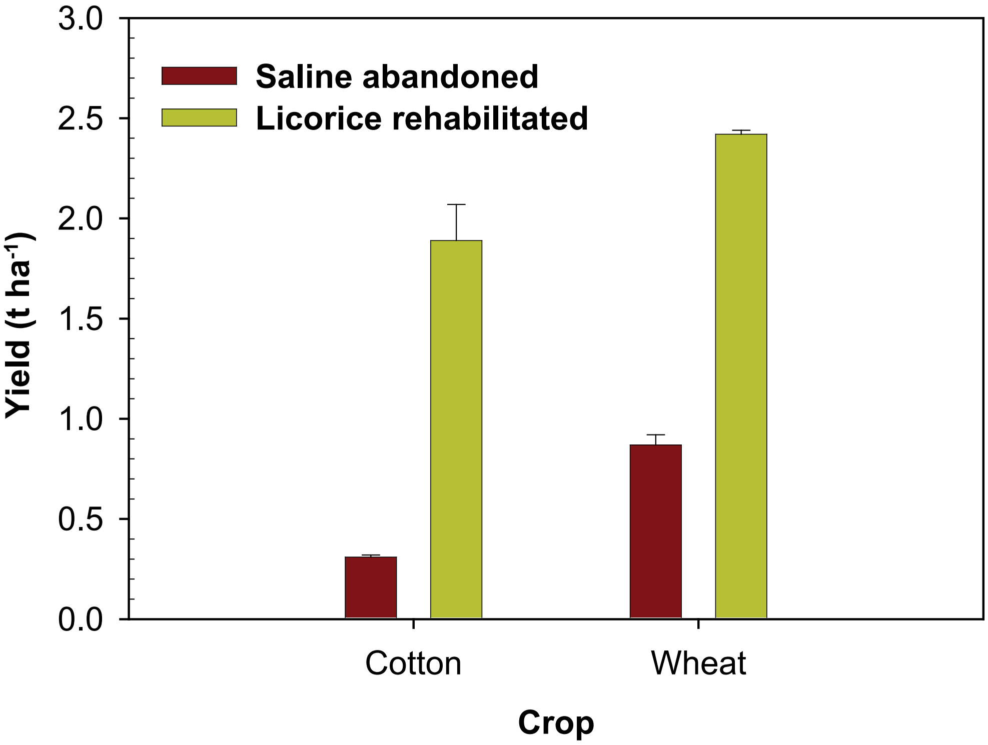
Rationale and Approach

With gradual increase in environmental degradation, energy shortages and poverty in salt-affected areas, particularly in Central Asian countries, there is a need for response in public policy and strong upturn to strengthen economic prospects in the affected areas (World Bank, 2013). Energy use in the region is generally inefficient at all levels including that of the end users, which leads to very high per capita domestic energy consumption and triggers poverty. Salt-tolerant tree plantations can be established on salt-affected degraded lands for phytoremediation purposes to reverse salt-induced land degradation and provide a source of energy for rural households.

Lamers et al. (2008) and Lamers and Khamzina (2008) evaluated the prospects of establishing agroforestry systems on saline wastelands in the lower reaches of the Amu-Darya River in Uzbekistan. They collected biomass data of three tree species: Russian olive (*Elaeagnus angustifolia* L.), Siberian elm (*Ulmus pumila* L.) and Euphrates poplar (*Populus euphratica* Oliv.). The data collected for five years were complemented with data of mature trees (15 to 20 years) growing naturally on the marginal land.

Based on the energy value of the tree species five years after planting, the 1-ha plantation of Euphrates poplar produced fuelwood to meet the average annual per capita energy needs of 89 people, followed by Russian olive (72 people) and Siberian elm (55 people) (Table 1; Lamers and Khamzina, 2008). The potential for capital investment in small-scale woodlots was assessed by considering annual fuelwood, fodder and fruit production, plus the stumpage value after 20 years. The benefit to cost ratio (BCR) and Net Present Value (NPV) were compared at 10, 16 and 24% discount rates. At 16% discount rate, the NPV for Russian olive was the highest (USD 13,924/ha), followed by Euphrates poplar

FIGURE 4. YIELDS OF COTTON AND WHEAT AFTER FOUR YEARS OF GROWING LICORICE COMPARED TO AN ADJACENT SALINE FIELD (NO SALINITY MANAGEMENT OPTION). VALUES ARE THE MEAN OF THE THREE REPLICATES WITH STANDARD ERROR (BASED ON DATA FROM KUSHIEV ET AL., 2005).



(USD 4,096/ha) and Siberian elm (USD 1,717/ha) showing a BCR of 7.8, 2.2 and 1.8 for these tree species, respectively (Lamers et al., 2008). This study demonstrated that tree plantations may provide positive returns to investment and significant economic and social benefits to land users. These findings suggest that there is an opportunity for capital investment in afforesting abandoned salt-affected lands with multipurpose tree species.

Although the financial assessment of afforestation is an important criterion, many additional factors such as risk assessment, familiarity with techniques to raise tree plantations and the availability of technical support influence the decision-making process of farmers in establishing agroforestry systems on salt-affected wastelands (Lamers et al., 2008; Lamers and Khamzina, 2008). The same applies to other regions of the world with salt-affected wastelands and demand for fuelwood.

Key Considerations for Implementation

Fuelwood prices are expected to rise in the study area and similarly in other areas in the region owing to ever-increasing energy prices and the growing dependency on fuelwood. Despite this apparently attractive option, many farmers in salt-affected areas are not in a financial position to accept the long payback periods involved when investing in timber production, hence a smaller number of farmers would more likely be interested in investing in long-term, sustainable and beneficial agroforestry systems. This situation warrants the involvement of agricultural extension services to motivate farmers and investors to integrate ecologically-appropriate tree production systems for areas that have been abandoned from cropping. Such an approach would require enabling political will and institutional awareness as well as involvement of the private sector and businesses, particularly those dealing with wood, pulp and paper. In addition, forestry policies must be reoriented and aligned to involve rural and urban users relying on trees for part of their income and/or domestic needs.

Large-scale Amelioration of Sodic Soils by Multiple Coordinated Actions

Rationale and Approach

There is widespread poverty and high dependency on agriculture for livelihoods in areas characterized by sodic soils in Uttar Pradesh State, India (Pandey et al., 2011). In collaboration with the World Bank, a pilot project on sodic soil amelioration was implemented to address poverty reduction. The main objective was to learn lessons from the pilot project for implementation of a larger project in the area. The major findings suggested the importance of monitoring and evaluation, the need to use flexible project management and participatory approaches, remodeling and maintenance of the main drain for drainage water management and the upgrading of farm to market roads. These findings were considered strongly in the design of the larger-scale project described below as the Uttar Pradesh Sodic Lands Reclamation Project.

TABLE 1. FUELWOOD PRODUCTION AND ESTIMATED ENERGY VALUE OF FIVE-YEAR-OLD TREE PLANTATIONS BASED ON CONVERSION INTO OIL AND COAL EQUIVALENTS (BASED ON DATA FROM LAMERS AND KHAMZINA, 2008).

CAPACITY PARAMETER	RUSSIAN OLIVE	SIBERIAN ELM	EUPHRATES POPLAR
Wood production (t/ha)	25.5	19.8	32.0
Stem wood energy (MJ/tree)	118	118	117
Branch wood energy (MJ/tree)	94	43	145
Biofuel capacity (MJ/ha)	487,623	369,886	601,036
Energy needs (people)	72	55	89

1 kWh = 3.6 MJ or 1 MJ = 0.28 kWh.

The Uttar Pradesh Sodic Lands Reclamation Project was implemented in Uttar Pradesh State from 1998 to 2007 for sustainable amelioration of sodic lands and prevention of further increases in sodicity in 10 selected districts with the highest concentration of sodic areas. The total cost was USD 286.6 million, largely financed by the World Bank with a loan of USD 194.1 million (World Bank, 2008). The project had seven major components: (1) on-farm amelioration of sodic soils using gypsum and organic materials through active community participation and well-coordinated government support; (2) remodeling and maintenance of main drains to improve the drainage networks for drainage water collection and disposal; (3) transfer of the sodic soil amelioration technology through a community-based, demand-driven system in the project districts; (4) repair and maintenance of farm to market roads; (5) human resource development and institutional capacity building of support services to facilitate the soil amelioration process; (6) adaptive research to verify and refine the available technologies to suit the specific needs of local farmers and to bring about sustainable increases in the productivity of sodic lands through the soil amelioration process; and (7) monitoring and evaluation to assess project progress in biophysical and socioeconomic dimensions and to find solutions to constraints in project implementation and achieving the desired outcome. Based on specific indicators, progress by the end of the project is presented in Table 2.

Regarding donor evaluation, the project was and remains highly relevant for areas where large-scale salt-affected soils are present and pose agricultural productivity and environmental constraints (World Bank, 2008). Most project outcomes were achieved and exceeded on many important fronts and efficiency was greater than expected. The project implemented an extensive training program for

TABLE 2. UTTAR PRADESH SODIC LANDS RECLAMATION PROJECT IN INDIA – PROGRESS ACHIEVED AND PROGRESS ASSESSMENT (WORLD BANK, 2008).

INDICATOR	PROGRESS ACHIEVED	PROGRESS ASSESSMENT
Amelioration sodic land	189,715 ha of sodic land ameliorated, out of which 126,990 ha of were severely affected, lying barren with no production; 93% of land under double cropping 3-5 years after amelioration.	54% more land amelioration than targeted in the project plan.
Expected increase in crop yields	Paddy yields increased from 0.9 to 3.5 t/ha and wheat yields from 0.4 to 3.0 t/ha-on the ameliorated land.	Paddy yield increase met the original target; wheat yield 11% higher than the target.
Maintenance main drains	Improved main drains supported drainage water collection and of transportation while also reducing the extent of the waterlogged area by 57%.	Satisfactory progress, but not fully accomplished.
Improvement in farm to market roads	1,112 km of rural roads upgraded, thereby significantly improving farm household income as farmers get better prices for their produce and have incentives to produce more.	412 km roads above the 700 km target were upgraded.
Poverty alleviation	48% of households under the poverty line compared to 72% households at the beginning of the project, i.e. 24% of the poor households crossed the poverty line threshold income level.	No target was set in the initial plan.
Farm income	Increase in average annual farm income by INR 5,947 for an average holding of 0.4 ha, i.e. USD 376/ha/yr (USD 1.00 = INR 39.5 at 2007 rates).	21% increase in farm income from the initial target.
Reduction in outmigration	Extra farm work on ameliorated land decreased annual outmigration for labor from 98 to 45 person days for men and from 38 to 5 person days for women.	No target was set in the initial plan.
Distribution benefits through landownership	126,542 villagers were allotted and/or provided possession of 58,660 ha land for greater security of tenure among marginalized of classes or the landless.	No target was set in the initial plan.
Community participation outcomes	Formation of 3,591 Site Implementation Committees (SICs), 48,167 Water User Groups (WUGs), 238 Farmer Field Schools (FFS), 3,213 Men Self Help Groups (MSHGs) and 7,193 Women Self Help Groups (WSHGs).	3% increase in SICs, 28% increase in WUGs, 105% in WSHGs; 8% decrease in MSHGs based on initial targets; no target was set for FFS.
Overall economics	Based on all the project costs, the Economic Rate of Return (ERR) of the overall project was 19.3%.	30% increase in ERR over the projected ERR (14.8%) at the time of appraisal.

different stakeholders to help them maintain progress made through the project. The important features of the project's participatory support system included rigorous contracting and monitoring of NGO engagement in all key village-level activities; community-based technology dissemination at the village level; participatory rural appraisal (PRA)-based planning; women's participation through self-help groups; transparent delivery of inputs to farmers; cost sharing by farmers via labor; and working with various stakeholders at all levels to develop convergence and sustainability strategies.

Gender mainstreaming was a key feature of the project. For addressing women's needs and empowerment, the project ensured women as co-title holders of all the newly allotted lands and established inclusive institutions (SICs and WSHGs) to make explicit the role of women in soil amelioration activities (Table 2). The project empowered women by enhancing their role in decision-making and provided them with opportunities for income generation.

Facilitating and strengthening of agricultural produce marketing from the ameliorated land was another important feature of the project. This was done by setting up 360 rural market hubs, out of which 46 were equipped with infrastructural facilities. About 200 project villages were linked with large markets while 338 project villages were linked with 125 milk routes with daily turnover of 31,754 liters. Opportunities for horticultural produce marketing were tapped through the development of 19 Primary Horticultural Cooperative Societies. One progressive farmer in each FFS was trained as a Marketing Animator to promote backward and forward market linkages (World Bank, 2008).

By the end of the project, a well-defined sustainability strategy had been developed and adopted. In this context, exit policy exercises were conducted by the farmers with the help of PRA techniques (developing an issues matrix and sustainability index for each village). The critical issues identified during exit policy exercises were addressed through follow-up exercises. A 'Convergence Matrix' was developed to sustain project impacts and maintain continuity of activities through convergence with various relevant departments and the private sector. This matrix helped in identifying the weak areas and fostering linkages with public and private sector agencies. The critical risks identified were timely rehabilitation of main drains, and maintenance of drains and roads to ensure the continuity of activities during the postproject period and for sustaining project impacts.

The project generated 26 million person days of additional employment opportunities due to crop area expansion, and intensification and diversification in the reclaimed sodic lands. At 300 days per year, this is equivalent to 86,710 additional jobs in the project area. Based on the success of the project, the Indian Government has initiated the next phase to ameliorate another 130,000 ha of sodic land in Uttar Pradesh from 2009 to 2017. With a total cost of USD 272.0 million, the project is largely financed by the World Bank with a loan of USD 197.0 million (Cook, 2014).

Key Considerations for Implementation

Sodic soil reclamation and improved farm income from the reclaimed lands in Uttar Pradesh had a positive impact on reducing poverty in the resource-poor sodic farm households along with other benefits. The success of this large-scale project was due to the lessons learned from the pilot project, which highlighted the significance of monitoring and evaluation, the need to use flexible project management and participatory approaches, and the importance of remodeling/maintenance of the main drain for drainage water management and the upgrading of farm to market roads.

Although the principles of sodic soil reclamation remain the same, it is important to run pilot project(s) elsewhere in the affected areas based on a range of local biophysical, economic and social conditions, and stakeholders' involvement, before considering implementation of large-scale reclamation project(s).

CONCLUSIONS AND FUTURE PERSPECTIVES

The case studies cover a broad range of examples across scales and regions to capture the diversity of potential business opportunities. These studies highlight the benefits and impetus for investing in saline water recycling and reuse as well as salt-affected land restoration in irrigated areas. To direct relevant future investments to achieve the desired success and economic returns based on the specific conditions and the resources available, there is a need for implementing a comprehensive program at the river basin or national level by taking into consideration water availability and quality, water politics – particularly for transboundary rivers, land-use options and strategy (including specific commitments to long-term renting of land to third parties or other countries), national bioenergy production strategies, national strategies for climate change management and national water and food security priorities.

Community mobilization and preparatory activities are essential for successful implementation of large-scale projects based on sound economic analysis, as evidenced by the case study presented in the section, *Plantation of Multipurpose Tree Species on Salt-affected Wastelands*, addressing sodic soil amelioration supported by a number of coordinated actions involving relevant stakeholders. A pilot study before implementing a large-scale project is very important in dealing with saline water and salt-affected soils from a long-term sustainability perspective. By providing lessons for large-scale project implementation, piloting can produce and test pro-poor systems, which can provide technically sound and transparent criteria for the focus area and beneficiary selection targeting the poor without excluding benefits to the wider community. The scaling up must take into account concurrent changes in target area conditions while using participatory processes and involving relevant institutions. Moreover, independent and timely monitoring and evaluation is the key to success through identifying issues and addressing them in a timely and efficient manner.

As saline water and salt-induced land degradation may occur both on and off site and affect livelihoods within and outside farming communities, there is a need for acting beyond typical farm-level salinity management approaches. This necessitates the development and implementation of national action plans such as a national salinity management strategy, drawing from a broad range of disciplines to ensure effective removal of barriers to adoption of sustainable land and water management and realize potential crop productivity and environmental gains, among others. The Murray-Darling Basin Salinity and Drainage Strategy Framework is a good example in this regard. As the framework is based on the biophysical and economic conditions in Australia, it should not be superimposed in a developing-country situation. There is a need to address the specific biophysical conditions and resources in a specific country and river basin along with socioeconomic dimensions as well as stakeholder consultation.

Investments in salt-affected irrigated zones can make a significant contribution to poverty reduction, economic and social development as well as efforts for achieving food security. In addition to socioeconomic benefits, there are environmental benefits that help mitigate climate change impacts by enhancing soil carbon sequestration. We believe that the time has come to harness the potential of saline water and salt-affected land resources as potential business opportunities while adding value to the business dimension through resilience against climate change.

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