# Sustainable Desert Agriculture Systems with Saline Groundwater Irrigation

Subjects: Agricultural Engineering

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Agricultural land expansion is a solution to address global food security challenges in the context of climate change. However, the sustainability of expansion in arid countries is difficult because of scarce surface water resources, groundwater salinity, and the health of salt-affected soil. Developing expansion and sustainability plans for agriculture requires systems thinking, considering the complex feedback interactions between saline groundwater, salt-affected soil, plant growth, freshwater mixing with saline groundwater, irrigation systems, and the application of soil amendments to alleviate the salinity impacts.

Keywords: desert agriculture ; salinity ; soil amendment ; systems thinking ; saline groundwater ; food security

## 1. Effects of Irrigation with Saline Groundwater

### 1.1. Impacts of Salinity on Crop Growth

The rise in food demand, coupled with the increase in water requirements to boost global crop production, amplifies stress on the limited available freshwater resources [1]. In arid and semi-arid regions, where the surface water is usually insufficient to meet the irrigation water demand, groundwater is used to make up for such deficits [2].

Salinity causes negative effects on both the soil and plant health. However, the extent of the effects on different plants can vary in degree. Also, there can be different levels of effects depending on the developmental stages of plant growth. During the early vegetative stages, crops are more sensitive to salinity and pronounced symptoms such as leaf stunting and tip leaf discoloration [3][4]. One of the major effects of salinity on the normal growth of plants comes from cellular shrinkage due to dehydration or physiological drought generated from osmotic stress caused by excessive salt ions [3]. Grains such as wheat and rice are especially susceptible to salinity in soil and water stress during the maturing stage—salinity could induce early flowering and deformed reproductive organs in wheat [5]. Both sodium and chloride ions adversely affect plant growth in the long term by limiting photosynthesis which results in the inhibition of the growth and development of agricultural crops [3].

Plants' roots are the main organ responsible for water and nutrient uptake, and the first interface to sense and respond to salinity stress. Therefore, investigating the root response of crops under salinity stress is important for developing climate-resilient crops [6]. Compared with shoot traits such as flowering time and yield, root traits are not a common plant breeding objective due to the inaccessibility of the root system and the lack of the requisite genetic data associating root phenology and molecular biology with adaptive responses to salinity [7]. However, the development of high throughput phenotyping platforms has recently permitted the association of root phenes with water acquisition from drying soil in cereals including rice [8][9] and maize [10].

Salt stress under osmotic or ion toxicity results in stunted root growth [11]; the degree of deterioration is associated with several factors—most importantly, species, salinity level, and soil type [12]. At the seedling stage, the inhibition of cotton root growth could be related to the elevated concentration of $Na^+$ at the expense of $K^+$—an effect that could be partially mitigated by the addition of $Ca^{++}$ [13]. Salinity, in most cases, damages the root system much less than the shoot, which results in a higher root/shoot ratio compared to control conditions [14]. Nevertheless, this phenomenon might not be a universal response within plants due to the variation in the range of salinity stress tolerance as seen in *Capsicum annuum* and *Chloris gayana*, where roots were damaged by salinity more than shoots [15]. Generally, it is thought that roots, unlike shoots, could be more sensitive to sodium ion toxicity rather than osmotic factors, particularly in the seedling stage of cereals such as maize and rice [16][17].

Root system architecture (RSA) is an important determining factor in a plant's capacity to access water and nutrients and, therefore, in crop productivity. Structural traits of the roots (e.g., total root depth, root angle, or lateral roots' number/branching density) showed a high degree of plasticity in saline soil from the early vegetative stage up to maturity and crop harvest. The shape of the RSA of mature plants is eventually determined by early root responses to gravity in saline soil [18]. Halo tropism or the disturbance of root gravitropism under salinity has been reported in many plants, such as *Arabidopsis*, sorghum, and tomato [19]. Interestingly, the primary roots of plant seedlings could escape or circumvent saline-affected soil by redirecting roots to access and extend into less salt-content soil located in a direction away from the main root vector angle [20]. Over the early stages of a crop plant's life cycle, high salinity inhibits primary root growth together with a number of lateral roots due to the reduction in the formation of meristematic tissue, called the lateral root primordium (LRP) [21]. On the other hand, Ref. [22] reported that lateral root growth increased as a result of increasing the salt concentration of irrigation water to 100 mM NaCl. Interestingly, the elevated increase in $Na^+$ uptake by the increased surface area of the emerged lateral roots showed no negative effects. The potential negative effects were apparently mitigated by a significant reduction in hydraulic water conductivity.

### 2.2. Impacts of Salinity on Soil Health

Physical, biological, and chemical characteristics of soil are all included in soil health. As a result, any impact on any or all of the soil properties will seriously harm the health of the soil. Furthermore, water shortage is highly pronounced in arid and semi-arid countries and has become a worldwide problem of increasing seriousness. Thus, low-quality water such as saline groundwater is commonly used to dominate water shortage [23]. Therewith, saline groundwater naturally has solutes of variable concentrations, and its application can be noticeably affected by soil and plant properties. Due to salt accumulation in the root area, irrigation with saline water generally causes increasing soil salinity and greater salinity threats to plant growth [24].

Furthermore, climate changes increase the intensity of the salinity problem. In reality, global warming leads to increased temperature and precipitation fluctuations, with consequent increases in evapotranspiration and the reduction of salt leaching [25]. Consequently, the presence of salt in the soil area increases. Groundwater salinization causes problems such as soil compaction [26], a reduction in the fertility of the soil [27], and, ultimately, a reduction in crop yield [28]. For example, the compaction of clay soil particles is affected by the valence of the adsorbed cation and the salt concentration. In general, the larger the valence of the adsorbed cation, the closer the cation is held to the clay particle [29].

For irrigation, water quality suitability needs to be determined. As pointed out earlier, freshwater—especially fresh groundwater—is rapidly diminishing [30], and the remaining water is becoming saline [31]. Therefore, it is necessary to consider the use of saline water for irrigation in the face of diminishing freshwater resources. Consequently, opportunities and challenges should be highlighted and should be focused on addressing soil salinity. Opportunities to alleviate salinity problems include adding improvements, cultivating salinity-tolerant varieties, irrigating in a timely manner, mixing fresh and saline water, and improving drainage and soil maintenance.

## 2. Soil Amendment to Increase Crop Production in Salt-Affected Soils

In semi-arid regions, such as Egypt, groundwater irrigation is a common alternative for desert agriculture, especially when surface water availability is limited [32]. However, the presence of excessive salinity in groundwater and soils can significantly reduce agricultural crop yields by triggering serious negative effects on soil properties and plant traits. This is a critical challenge to agricultural producers and policy-makers for achieving sustainable desert/biosaline agriculture and food security [33]. The effectiveness of the technical options available to minimize the salinity effects is unclear, however, their implementation is necessary for the planning of desert agricultural systems using saline groundwater.

With the use of saline irrigation water, various approaches to improve crop production against salinity stress have been implemented. These include (1) the planting of salt-tolerant crops, (2) the use of more efficient irrigation methods (e.g., drip irrigation system), (3) salinity leaching, and (4) treatment and amendment of saline soil [34][35]. In arid and semi-arid regions, the salinity leaching method with (artificial) drainage is typically used to manage soil salinity [35]. By ensuring an effective salt "balance" between soil drainage water and the plant root zone, agricultural crop yields can be maintained at adequate production levels. In this approach, the irrigation and/or drainage specialist determines an appropriate moisture leaching fraction that results in an acceptable crop yield at a reasonable cost [36][37]. Thus, this option produces the effects of not only removing the salinity from the root zone physically, but also recharging the groundwater and managing the water table level [35]. However, in locations where only saline irrigation water is available and freshwater availability is limited, the addition of specific soil amendments may be the only cost-effective alternative for sustaining agricultural crop production levels [38].

Soil amendments have been widely employed to improve poor soil quality—including the negative effects of soil salinity—for various crop types [39]. Soil amendments can be classified into two types: (1) organic amendments, including solid waste compost, fly ash, and biochar; and (2) inorganic amendments, such as gypsum, langbeinite, and zeolite [39][40][41][42]. One of the common soil amendments is the application of biosolids, i.e., the residual organic solids generated from the physical and biological treatment of municipal wastewater [43]. Land-applied biosolids improve both the aeration and drainage capacities of saline soils through porosity enhancement [44]. Moreover, the organic fraction of biosolids increases the saline soil's available water holding and cation exchange capacities [45]. However, biosolids land application for agricultural production is not legal in Egypt, because the biosolids contain organic pollutants that pose significant risks to public and environmental health [46]. In other countries, this practice has strict regulatory limits on human pathogens, heavy metals, and emerging contaminants such as microplastics [47][48][49][50].

Numerous studies have reported enhanced soil quality and crop productivity following biochar land application through quantitative investigations for different types of soils [51][52], feedstocks [53][54][55], and crops [51][56][57][58]. Previous studies, including [58][59][60], have also investigated the agricultural effects of biochar on the soils in Egypt. For example, Ref. [61] investigated the crop productivity effects of biochar application to sandy soils in Egypt under deficit irrigation water conditions. They suggested an optimal biochar rate that produced about 25% reduction in the irrigation requirement. Ref. [62] examined the effects of biochar—derived from different feedstocks (rice straw and soybean)—on the fertility of reclaimed sandy soil in Egypt and suggested a biochar rate that yielded the largest growth and productivity of wheat in the sandy soil.

Unlike biosolids, the acute and long-term effects of biochar land application on public health, economics, and the environment have not been extensively studied. A few studies have provided insight into some of the apparent tradeoffs that exist between biochar's beneficial use and public health. For example, while biochar produced from maize cobs has been found to be effective in improving soil fertility in developing countries, the air pollutants associated with pyrolytic emissions—namely, $PM_{10}$ (particulate matter of fewer than 10 microns) and carbon monoxide (CO) —have had serious deleterious effects on human health in those communities [63]. Unfortunately, technologically advanced pyrolytic kilns with air emission controls are financially unavailable for many of these agricultural producers [63]. A full understanding of the tradeoffs between social, economic, and environmental impacts and the agricultural benefits associated with land application of biochar is required if this approach to mitigating soil salinity is to become standard agricultural practice. To quantify and predict such tradeoffs, it is necessary to establish a science-based mechanistic and systemic understanding of how biochar processing (raw materials and pyrolytic conditions) affects the final biochar characteristics, and of how those characteristics, in turn, impact soil properties and crop yields.

## 3. Challenges for Sustainable Desert Agriculture Systems

### 3.1. Systems Thinking to Understand Feedback Processes in Desert Agricultural Systems

**Figure 1** shows a Causal Loop Diagram (CLD) showing an example of the feedback processes that can be considered for desert agricultural systems in Egypt. The CLD is commonly used to qualitatively understand the dynamic feedback interactions that are produced by critical system components and their causal relationships [64][65]. In the CLD, the positive label on a causal link implies that an increase/decrease in the state of a component causes an increase/decrease in the state of a connected component. The negative label indicates that an increase/decrease in a component causes a decrease/increase in a connected component. Thus, these positive and negative causal links create feedback loops, which determine the system behaviors such as reinforcing ('+') or balancing ('−'). Further details of the CLD can be found in [65]. The specific description for the feedback interactions in **Figure 2** is as follows:

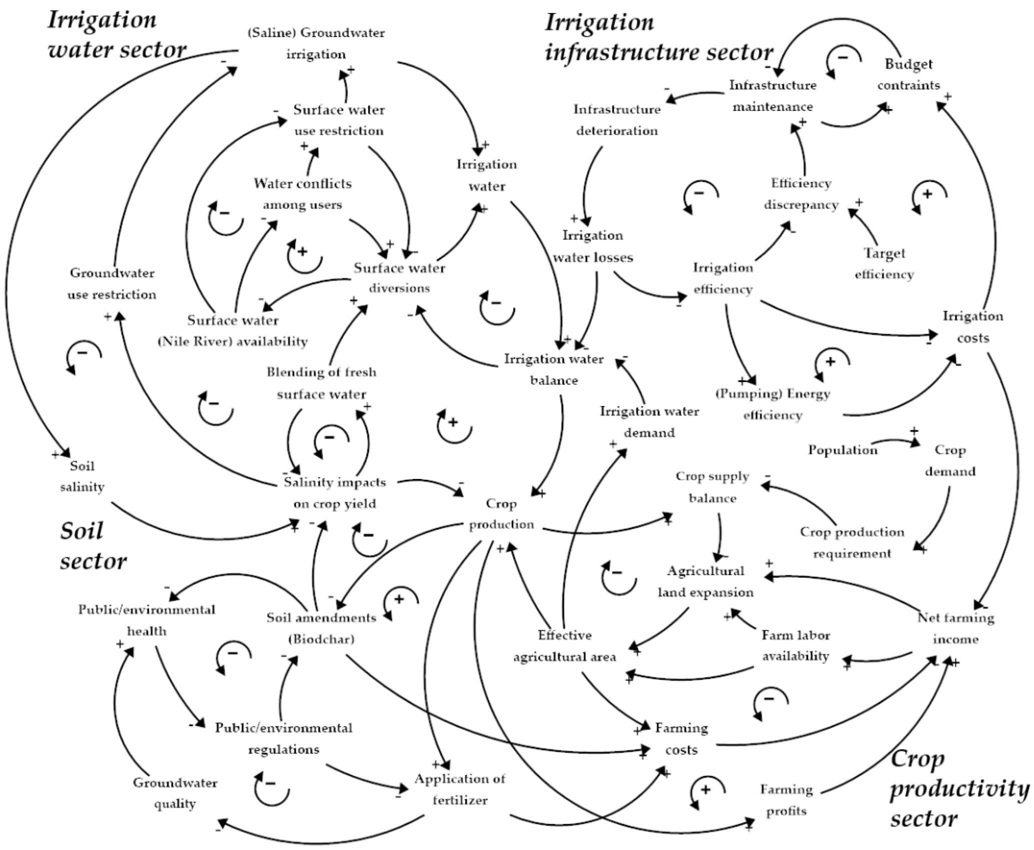


**Figure 1.** An example of a CLD for feedback interactions between the irrigation water, irrigation infrastructure, soil, and crop productivity sectors.

The interactive feedback processes in desert agricultural systems can act as resources reinforcing or constraints balancing the systems' behaviors (e.g., irrigation water availability and crop productivity). The dynamics and complex interactions of the feedback processes can create the unexpected, uncertain performance of the agricultural systems—which is called the "emergent property (phenomenon)" in complex systems [64][66]. An example of the emergent property would be the level of soil fertility for plant growth and productivity, which is determined by the physical, chemical, and biological interactions between the plant (e.g., crop types and nutrients), animal (e.g., soil organisms and animal health), human (e.g., cultivating intensity and food production), and climate dimensions [67]. Failure to consider the structural and feedback interactions can bring misunderstanding of the counterintuitive consequences (emergent property) from the implementation of a desert agricultural system with blending diversions of the Nile River with saline groundwater and/or the application of soil amendments for improving agricultural crop production. Thus, the decision-making process on a sustainable desert agricultural system needs to follow an integrated and holistic view, considering the nonlinear and dynamic feedback interactions across its subsystems and associated factors [65][68][69][70][71].

### 3.2. Need to Address Dynamics in Drivers

Feedback processes and their interactions are directly affected by dynamic external drivers such as climate and socioeconomic changes (e.g., market prices, population growth, and domestic water demand), energy availability (e.g., energy crisis), and policies (e.g., environmental regulations and subsidies), which can induce system behaviors that are unexpected in the decision-making process [72][73][74][75].

Rising sea levels due to climate change can also increase the intrusion of salt water into the shallow aquifer and, in turn, lead to an increase in groundwater salinity—e.g., the increase in salinity in the Nile Delta region due to climate change is anticipated to be about 27% [76]. Thus, with the increased use of groundwater irrigation, salt water intrusion exacerbates soil salinity and eventually, will limit the use of saline groundwater, which affects the feedback process related to irrigation water availability and crop productivity.

The projections of climate change in Egypt indicate an increase in temperature of 3.1 °C to 4.7 °C [77][78]. This temperature rise can produce a significant increase in evapotranspiration, which can increase by 4% as a result of a 1 °C temperature rise in Egypt [76]. The increased evapotranspiration increases irrigation demands and elevates the salinity of the soil and groundwater, which will limit the use of groundwater for irrigation [79]. In addition, climate change has direct impacts on the growth, productivity, and quality of most crops [75][76].

Egypt is experiencing a rapid increase in population growth. The population has doubled since the mid-1980s and the urbanized areas have increased substantially. The increasing food demand as a result of population growth, urbanization, and an increase in living standards has highlighted the need to expand agricultural production. This expansion requires more irrigation water, which will exacerbate the competition among the end-users of the Nile River.

## 3.3. The Need for a System Dynamics Approach in Decision-Making

The agricultural systems built on reclaimed desert lands, as water-agriculture-socioeconomic systems under dynamic and various drivers, are inherently complex. As described earlier, these systems can have delayed, unintended, and unexpected consequences in system behaviors arising from feedback processes with management interventions [80]. Thus, the planning of saline groundwater use for desert agricultural systems needs to be addressed with systems thinking and long-term strategies to identify the emergent properties among the water, agriculture (e.g., soil, biophysics, and infrastructure), environment (e.g., climate), and socioeconomic sectors and to minimize the unintended system behaviors [80][81][82].

Systems thinking considers multifaceted and interacting components in a holistic view for planning a system [81]. In this regard, the system dynamics (SD) approach is uniquely suited to understanding and analyzing the complex, nonlinear, and dynamic behaviors of agricultural systems governed by complicated interacting feedback processes with a time delay [68][80]. The SD approach emphasizes the relationships and interactions among the system's components rather than considering the individual components in isolation [65][68]. The integrative characteristics of the SD approach allow for the coupling of the physical, socioeconomic, and environmental components that comprise agricultural systems. Thus, the SD approach underlines the engagement of multifaceted stakeholders—who are involved in the planning of agricultural systems impacted by saline groundwater irrigation and the addition of soil amendments to support agricultural production in desert lands—and their inclusive decision-making with transparency and multiple criteria [83].

## 3.4. Sustainable Desert Agricultural Systems with Saline Groundwater Irrigation

### 3.4.1. Diversification and Decentralization in Irrigation Systems

Reclaiming desert land for agriculture with saline groundwater irrigation will pose sustainability challenges for maintaining the required agricultural productivity given limited water and financial resources and uncertain, dynamic drivers, as described above. A simple measure for sustainable irrigation and agriculture is the modification of cropping patterns, as a demand-side adaptation option, that can result in reduced irrigation water demand [75][84]. However, modification of cropping patterns can be misinterpreted due to the need to increase the security of the targeted agricultural crops [75]. In this context, an increase in water resources and system efficiency is a more effective measure for sustainable agricultural production than tracking the level of cropping pattern modification [75].

However, the drivers that affect irrigation have high statistical uncertainty [85]. The uncertainty in climate change further exacerbates the complexity of predicting the climate impacts combined with socioeconomic changes—e.g., the variation in the flow of the Nile River from −60% to 45% for multiple general circulation models (GCMs) [86], or in the range from a 30% increase to a 77% decrease [87]. The uncertainty in local drivers can lead to debates and conflicts among stakeholders over their impacts and importance during the decision-making processes [88]. Thus, addressing the uncertainties of the various drivers and their impacts is the primary challenge in decision-making for sustainable irrigation systems in reclaimed desert agriculture.

### 3.4.2. Urban Water Demand Management

Another strategy for sustainable irrigation systems in desert agriculture is urban water demand management with optimal allocation of water resources [89][90]. This option can mitigate the diversion demands on the Nile River and the competition among the end-users by reducing urban water consumption [91]. However, the water requirements of various sectors are different and are changing over time. The current water allocations of the Nile River and groundwater may be inadequate for future water demands. In this regard, diversification and decentralization options (e.g., distributed alternative water sources) in urban water systems, along with the stepwise tradeoffs between urban and agricultural water resources, will also help improve the availability of irrigation water resources in the long term, considering the dynamics and uncertainties of climate and socioeconomic changes.

### 3.4.3. Sufficient Energy Availability

An increase in energy consumption in Egypt due to rapid population and economic growth can limit the operation and efficiency of the irrigation infrastructure (e.g., pumping energy for groundwater extraction) under limited energy availability. In addition, the use of diversified water resources for sustainable irrigation water or desalination technologies (e.g., reverse osmosis, electrodialysis, nanofiltration, distillation, capacitive deionization, or solar humidification and dehumidification) to dilute the salinity in groundwater may also lead to an increase in the energy consumption (requirements) of the desert agricultural systems [92][93][94][95][96].

#### 3.4.4. Smart Irrigation System

Improving irrigation systems' efficiency will also contribute to sustainable water irrigation and desert land agriculture. In this regard, a smart irrigation system with sensors and controllers can be considered [97]. Many agriculture systems irrigate water at a specific or regular time and duration via timers of manual controllers. This type of irrigation system has contributed to the waste or over-irrigation of water without considering the irrigation requirements based on climate and soil conditions—e.g., about 30% of irrigated water is wasted [98]. Smart irrigation systems with sensors (e.g., soil moisture sensors), communication, analytics, and controllers (e.g., remote timers) can collect data on soil conditions and irrigation facilities in real time and predict real-time irrigation requirements along with climate conditions such as temperature, humidity, antecedent rainfall, and winds [99][100][101].

#### 3.4.5. Active Participation of Stakeholders

Many agricultural stakeholders, including farmers and system managers, have learned how to decide and adjust their plans and adaptation activities based on their practical experience. In this context, sharing their experiences and portfolios of adaptation strategies among multiple stakeholders can substantially and effectively improve the stakeholders' knowledge and adaptation capacities [102]. Thus, there is a need to incorporate strategies for learning, including the creation of educational environments that meet the needs of multiple stakeholders faced with desert land agricultural system planning under uncertainty.

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