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Soil Salinity and Sodicity as Particular Plant/Crop Stress Factors

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INTRODUCTION

Salinity and sodicity problems are common in arid and semiarid regions, where rainfall is insufficient to leach salts and excess sodium ions out of the rhizosphere. In addition, these areas often have high evaporation rates, which can encourage an increase in salt concentration at the soil surface.

The presence of a cliche horizon and/or a cemented hardpan layer at varying depths plus insufficient precipitation for leaching often adds to the salt accumulation in these soils. Newly established irrigation projects, with improper planning and management practices, may also add salts to soils [1].

Soil salinity and sodicity problems are present in nearly every irrigated area of the world and also occur on nonirrigated croplands and rangelands. Thus, virtually no land is immune from salinization. Therefore, for sustaining life on earth, control of these problems and finding new ways to utilize these extensive saline and sodic soils and water resources, at least for agricultural purposes, are vital and urgent. Reclamation, or at least minimizing the effect of salinity and/or sodicity, is important and necessary. In this respect, proper utilization of water for both plant growth and soil salinity and sodicity control is probably of the greatest importance.

The main focus of this introductory chapter is to summarize general information on salt-affected (saline and sodic) soils and factors influencing their formation and reclamation.

SIGNIFICANCE OF SOILS IN RESPECT OF CROP STRESS

As far as all the crops are grown on soils, soil properties have substantial influence on the life conditions of plants and crops. In nature, usually particular plant species grow on specific soils. Thus, specific relationships exist between a particular soil and the vegetation cover of that specific soil. For example, Kreeb et al. [2] investigated soil and vegetation relationships associated with alkaline-saline soil surfaces.

Plant development and successful crop production require proper soil conditions, including adequate water and nutrient supply. Unfavorable soil conditions (environmental stress [3–5], salinity and/or sodicity [6,7], inadequate nutrient supply [8,9]) have an adverse effect on the life of the plants, sometimes seriously hindering their effective production.

Based on the above facts, we can speak of stress factors originating in the soil; that is, such unfavorable soil conditions which cause, or contribute to, the stress factors that plants and crops are exposed to.

It is impossible to list all or most of such factors in a short introductory chapter. Therefore, we limit the range of this chapter to a general description of soil behavior and its function in nature and production as well as to an outline of one of the most serious factors originating in salt-affected soils. For more in-depth information regarding salt-affected soils, the readers are referred to the more comprehensive available sources [10–31].

PLACE AND ROLE OF THE SOIL IN NATURE

It is generally accepted that the soil is a substantial part of the environment, comprising different substances and forming a special kind of ecosystem inside the given ecosystem, with various properties and attributes. It is also accepted that the soil of the continents is of high diversity, which is dealt with by several branches of soil science; for example, taxonomy, classification, survey, and mapping.

The soil, or the pedosphere, which is an environmental synonym of the soils of a given territory, has a specific place in nature. It is a natural body, similar to rocks, waters, or biota in the sense that they too have their own materials, mass and energy fluxes, development, and regularities. This fact should be mentioned because, not only in newspapers but also in technical literature, soils are frequently treated either as living substances or as nonbiological substances. Neither of these approaches is correct, because one of the characteristics of the soil is its complexity, the fact that it contains both living and nonliving substances, forming as a result of both biotic and abiotic processes.

The soil as a natural body is inseparable from the rocks and the crust of weathering on the surface of the continents from which it has developed, on the one hand, and from the biological processes on the other hand. The main characteristics that distinguishes the soil from the rocks is the result of biological processes: the production of organic matters by the activities of microorganisms, plants, invertebrates and other animals, and finally human beings which transforms the rocks into soils capable of supplying plants and crops with nutrients and water.

The processes of soil formation started concurrently with the appearance of life on the continents and continued during the billions of years of interactions between living substances and rocks under the influence of climatic conditions, with particular regard to the action of water, geomorphological patterns, and the time factor. As a result of their interactions, specific mass and energy fluxes formed the different soil types in various environmental conditions.

With the appearance of the human race on the face of the earth, even changes in the environment became different. Owing to human activities, the natural processes affected by biotic and abiotic factors accelerated and several others which were unknown or minimal before developed.

The role of soils in nature is complex and many sided, including biospheric, hydrospheric, and lithospheric functions. Their interaction is illustrated in Figure 1 [11], which clearly shows that

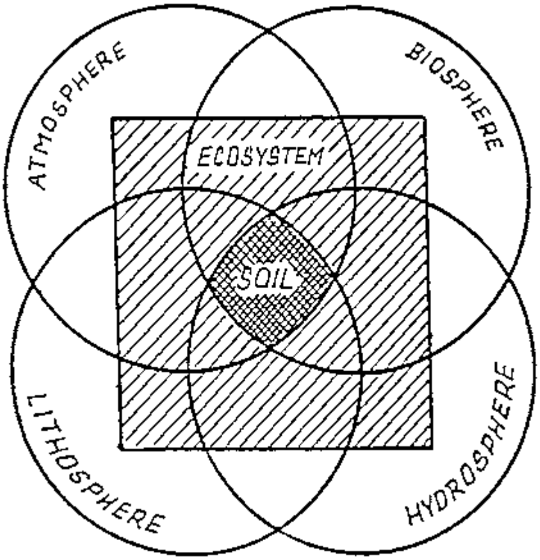

Figure 1 Schematic diagram of the interaction of lithosphere, atmosphere, biosphere, hydrosphere, ecosystems, and soils. (From Ref. 11.)

the soil is a specific body related to the ecosystem. Even the word *soil* is very often used as a synonym of ecosystem when characterizing the given ecological conditions in a certain place. If we want to be precise, we must agree that the ecosystem includes the pedon, in other words, the soils. However, the soil includes different phases (solid, liquid, gaseous), living and nonliving substances, plants, animals, and microbes and has its own energy and material fluxes. Therefore, it can be considered an ecosystem in itself. In this respect, when speaking of soils versus their plant cover, we can consider the soils of a given location as the basis, ladder, and foothold, for instance, in savannas, or in the tropical belt, a well-defined plant cover develops and very often the soil properties promote or limit the living conditions of certain plant species or associations.

Based on the above considerations, it can be accepted that certain soil types, when discussed as the habitat for certain plant associations, are often named as the ecosystem of the plant association concerned, as the pedon includes, apart from the plants, most of the components of the ecosystem.

Evidently the soil, as a specific natural entity, is far from being identical with the vegetation and, in spite of their close correlation, direct conversion between soil types and vegetation is hardly possible. Still there are soil types which, more or less, determine the ecological function for certain types of vegetation either by providing beneficial conditions for its development or by limiting the ecological conditions for other types of vegetation.

This is perhaps best demonstrated in the case of salt-affected soils where high electrolyte contents of extreme pH conditions limit the development of the majority of plants and serve as a habitat only for such species which can survive or tolerate the unfavorable conditions caused by the salinity and alkalinity of the soil. For example, the grass *Leptochloa fusca* that grows vigorously on the salt-affected soils can tolerate extremely saline and sodic (alkaline) conditions [25]. This species is also well adapted to the waterlogging encountered on saline and sodic (alkaline) soils. Other investigators [2,7,32,33] have also reported on the soil and vegetation relationships that specific plant types are adapted and growing on specific habitats. In such respects, salt-affected soils can be considered as habitat or ecosystems for halophytes and, if we agree on this, correlations can be found between the different types of salt-affected soils and their flora and fauna as components of the ecosystem.

In order to cast light on both the theoretical and practical aspects of such considerations, it is necessary to describe briefly the properties and grouping of salt-affected soils with regard to the possibilities of the occurrence and distribution of halophytes and xerophytes developing on them.

EXTENSION AND GLOBAL DISTRIBUTION OF SALT-AFFECTED SOILS

Nearly 10% of the total land surface is covered with different types of salt-affected soils. Table 1 demonstrates the distribution of salt-affected soils in the world [34], and it shows that no continent on our planet is free from salt-affected soils. They are distributed not only in deserts and semidesert regions, but also frequently occur in fertile alluvial plains, river valleys, and coastal areas close to densely populated areas and irrigation systems [11–14,16,17,26].

Figure 2 shows the distribution of salt-affected soils throughout the world [12,17].

TABLE 1 Salt-Affected Soils on the Continents and Subcontinents

Continent	Area (millions ha)
North America	15.7
Mexico and Central America	2.0
South America	129.2
Africa	80.5
South Asia	87.6
North and Central Asia	211.7
South-East Asia	20.0
Australasia	357.3
Europe	50.8
Total	954.8

FIGURE 2 Global distribution of the salt-affected soils.

DEVELOPMENT AND GROUPING OF SALT-AFFECTED SOILS

In spite of the fact that the properties and attributes of salt-affected soils have been well known for a long time, it is appropriate to give a brief definition of this group of soils right at the start, because the salinity and sodicity (alkalinity) as well as the acidity of soils are substantial stress factors seriously affecting the productivity of the land [3–9,12,17,29,35–38].

Salt-affected (i.e., saline, saline-sodic, and sodic) soils usually have low biological activity both because of osmotic and ionic effects of salts and due to limitation of carbonaceous substrates. Rao and Pathak [39] reported that microbial growth was depressed in sodic (alkali) soils due to, at least in part, limitation in carbon substrate (carbon stress) and in saline soils due to salt stress.

For detailed information on the formation of salt-affected soils, the readers are referred to Szabolcs [11,12] and Pessarakli [17].

Salt-affected soils can be characterized as soils formed under the dominant influence of different salts in their solid or liquid phases, which will then have a decisive influence on the development, characteristics, physical, chemical, and biological properties, and eventually the fertility of the soil. Whenever and wherever this phenomenon occurs, it produces specific formations of soils where the high electrolyte concentration and its consequences overshadow the former soil-forming processes or former soil properties and environmental conditions, often radically changing them.

High electrolyte concentration is the only common feature of all salt-affected soils. Their chemistry, morphology, pH, and many other properties may be different depending on the character of salinization and/or alkalization.

Salt-affected soils, in the broader sense, can be divided into the following groups:

1. Saline soils that develop under the influence of electrolytes of sodium salts with nearly neutral reaction (dominantly Na_2SO_4, NaCl, seldom $NaNO_3$). These soils occur mainly in arid and semiarid regions and form a major part of all the salt-affected soils of the world. High contents of soluble salts accumulated in these soils can significantly decrease their value and productivity.
2. Sodic (alkali) soils that develop under the influence of electrolytes capable of alkaline hydrolysis (mainly Na_2CO_3 and $NaHCO_3$ and seldom Na_2SiO_3 and $NaHSiO_3$). This group is well extended in practically all the climatic regions from the humid tropics to beyond the polar circles and their total salt content is usually lower than that of saline soils, sometimes even strongly sodic (alkaline). Virgin sodic (alkali) soils have a high pH and high exchangeable Na and are often barren. Sodic soils exhibit poor physical conditions that adversely influence water and air movement in the soils. Sodicity causes soil erodibility and impairs plant growth [27].
3. Salt-affected soils that mostly develop owing to the presence of $CaSO_4$ (gypsiferous soils) or, rarely, in the presence of $CaCl_2$. Gypsiferous soils can mainly be found in the arid and semiarid regions of North America, North Africa, the Near, Middle, and Far East, and also in Australia.
4. Salt-affected soils which develop under the influence of magnesium salts. This group occurs in arid, semiarid, and even semihumid regions and has a particular significance, especially those soils which have a heavy texture.
5. Acid-sulfate soils whose salt content is composed mainly of $Al_2(SO_4)_3$ and $Fe_2(SO_4)_3$. This type of salt-affected soils is broadly extended in the tidal marsh areas along the seashores of all the continents. These soils are particularly common in, for example, North Europe, the western and eastern coastlines of Africa, and along the coastline of Southeast India, and develop on sulfurous marine sediments.

Inland acid-sulfate soils can also be found in different areas of the world, such as the western territories of the United States, Asia Minor, and China. Such soils developed as a result of fluvial glacial processes and have had no connection with seashores in recent geological times.

Evidently the different groups of salt-affected soils have diverse physicochemical and biological properties besides the one they have in common; that is, a comparatively high electrolyte content.

The grouping of the salt-affected soils and their properties causing plant and crop stress are presented in Table 2. The five groups in Table 2 represent the formations of different salt-affected soils described above, indicating their chemical types, the environmental conditions where they dominate or occur, the pattern of their main adverse effect on production, and the basic methods of their reclamation. For detailed information on formation and reclamation of salt-affected soils see Szabolcs [11,12] and Pessarakli [17].

In Table 2, the adverse properties of different salt-affected soils causing crop stress are also included. From these, it is clear that, in various groups, different properties are responsible for hindering the development of plants and crops by causing stress.

In saline soils, it is the high salt concentration in the solid and liquid phases which results in high osmotic pressure, hindering the normal development of plants. the stress factor is the salinity with all its disadvantageous consequences of plant life. Apart from this, some compounds of the salt content of these soils, for example, chlorides as toxic elements, also act as one of the stress factors.

In sodic (alkali) soils, as a rule, not the high salt concentration but the sodic (alkaline) pH value is the stress factor, particularly in cases where there is a high concentration of sodium carbonate in the solid and liquid phases of the soil. The high pH hinders the life function of crops and limits their development.

In another group of sodic (alkali) soils, which sometimes does not have very alkaline pH value (solonetz type), the comparatively low concentration of sodium salts capable of sodic (alkaline) hydrolysis constitutes a stress factor through its action, resulting in poor water physical properties in the soil. As a consequence of this phenomenon, the wilting point in the soil increases and the plants suffer from water deficiency, even in wet soils, owing to the swelling of clay saturated with sodium ions.

In magnesium soils, which have not been adequately studied, the combination of toxic effect, calcium deficiency, and poor soil physical properties are the stress factors.

In gypsiferous soils, the acidic pH, and sometimes the toxic effect of the high gypsum content, contribute to the appearance of stress factors for plant and crop life in areas with large extensions of intensively gypsiferous soils.

In acid-sulfate soils, the very high acidity, with a pH sometimes below 2, poses stress with all the adverse effects of extreme acidity. Furthermore, the high aluminum content of the soil solution has an intensive toxic effect. Apart from this, the temporary or permanent waterlogging in such soils acts as a stress factor hindering the normal air and nutrient regimen necessary for plant life in these soils.

Besides the salt-affected soils developing as a result of natural soil-forming processes, the so-called secondary salt-affected soils have an increasing importance that is both scientific and practical. Secondary salt-affected soils are those which have been salinized owing to manmade factors, mainly as a consequence of improper methods of irrigation. The extension of secondary salt-affected soils is rather sizeable, and this adverse process is as old as irrigated agriculture itself. Ancient civilizations in Mesopotamia, China, and Pre-Columbian America fell as a consequence of the salinization of irrigated land. The process is also advancing vigorously at present, and more than half of all the irrigated lands in the world are under the influence of secondary salinization and/or alkalization.

When speaking of the manmade factors of salinization, we also have to mention potential salt-affected soils which are not salt-affected at present, but in case of the extension of irrigation, deforestation, overgrazing, and other manmade measures, can and will be salinized unless the necessary preventive procedures are undertaken in due time. No global records are available of the size of potential salt-affected soils; however, the area that they cover is larger than that of existing salt-affected soils.

Secondary salt-affected soils can be divided into the following two categories: secondary

TABLE 2 Grouping of Salt-Affected Soils and Their Properties Causing Plant and Crop Stress

Type of salt-affected soils	Electrolyte(s) causing salinity and/or alkalinity	Environment	Properties causing plant and crop stress	Methods for reclamation
Saline	Sodium chloride and sulfate (in extreme cases nitrate)	Arid and semiarid	High osmotic pressure of soil solution, toxic effect of chlorides	Removal of excess salt (leaching)
Alkali	Sodium ions capable of alkaline hydrolysis	Semiarid, semihumid, and humid	High (alkali) pH, poor water physical conditions	Lowering or neutralizing the high pH by chemical amendments
Magnesium	Magnesium ions	Semiarid and semihumid	Toxic effect, high osmotic pressure, Ca deficiency	Chemical amendments, leaching
Gypsiferous	Calcium ions (mainly $CaSO_4$)	Semiarid and arid	Low (acidic) pH toxic effect	Alkaline amendments
Acid sulphate	Ferric and aluminium ions (mainly sulfates)	Seashores and lagoons with heavy, sulfate-containing sediments, diluvial inland slopes and depressions	High acidity and the toxic effect of aluminium	Liming

formation of salt-affected soils caused by irrigation and secondary formation of salt-affected soils caused by human activities other than irrigation.

Secondary Formation of Salt-Affected Soils Caused by Irrigation

In spite of the negative experiences, the salinization of irrigated and surrounding areas has not diminished. On the contrary, it is still on the increase.

According to the estimates of the Food and Agriculture Organization (FAO) and the United Nations Educational, Scientific, and Cultural Organization (UNESCO), as much as half of all the existing irrigation systems of the world are, more or less, under the influence of secondary salinization, alkalization, and waterlogging. This phenomenon is very common not only in old irrigation systems but also in areas where irrigation has only recently begun.

According to the estimates of the above-mentioned agencies, 10 million hectares of irrigated lands are abandoned yearly because of the adverse effects of salinity due to irrigation, mainly secondary salinization and alkalinization.

The mentioned losses and damages are not evenly distributed among the irrigating countries. In some of them, the damage may be relatively small, whereas in others, it actually constitutes the major problem in agriculture or even in the national economy of the country in question. In this respect, unfortunately, there are countless sad examples. In Pakistan, Ahmad [40] carried out statistical analyses in respect of secondary salinized land. According to his data, out of 35 million acres (approximately 16 million ha) of total irrigated territory, salinized areas account for 5.3 million acres (approximately 2.4 million ha) after a few years of irrigation. He indicated among the causes of secondary salinization in Pakistan the joint effect of irrigation and ground water. According to Zavaleta [10], practically all irrigated alluvial soils in Peru show the features of salinity and sodicity (alkalinity). It is known from FAO reports and the papers of Kovda [41] that more than 40% of irrigated soils in Iraq and Iran is affected by secondary salinization. In a country report on salinity in Syria, the FAO [42] estimated the adverse effects of salinity as follows:

1. In more than 20,000 ha, salinity developed to a level where these soils had to be taken out of cultivation, and the loss is estimated at a total of 30,000 tons of cotton per year.
2. In about 30,000 ha, the yield decreased by 50%, and the total loss is estimated at 20,000 tons of cotton per year.
3. In about 60,000 ha, the yield decreased by 20%, and the total loss is estimated at about 18,000 tons of cotton per year.

At present, no continent is free from the occurrence of this very serious phenomenon. In Argentina, 50% of the 40,000 ha of land irrigated in the 19th century are now salinized. In Australia, secondary salinization and alkalization take place in the valley of the River Murray, and in Northern Victoria, 80,000 ha have been affected. The same phenomena can be observed in Alberta, Canada, and similar processes have been recorded in the northern states of the United States, where irrigation was introduced much later than in the dry western states. It is noteworthy that these last examples, and many other irrigated regions, are far from being arid areas, and the majority of salt accumulating is associated with the sodium salts capable of sodic (alkaline) hydrolysis and not with the neutral sodium salts that we are familiar with in desert and semidesert areas.

Secondary Formation of Salt-Affected Soils Caused by Human Activities Other Than Irrigation

When speaking of secondary salinization, most people have irrigation and drainage in mind. However, there are also other anthropogenic factors causing these adverse phenomenon. It is true that the majority of secondary salt-affected soils develop as a result of improper methods of irrigation, but there are other human effects which more and more often trigger this process in many places both in arid and humid areas.

Some of these anthropogenic processes include, but are not limited to, the following:

Overgrazing

This process occurs mainly in arid and semiarid regions, where the natural soil cover is poor and scarcely satisfies the fodder requirement of rather extensive animal husbandry. If the natural vegetation is sparse or annihilated on account of overgrazing, progressive salinization develops and, step by step, the scarcity of the plant cover becomes increasingly pronounced. Sometimes the process ends in desertification, because even the poor pasture diminishes and no other fodder resources are available. According to Theunissen [43], the gradual decline in the ecological condition of natural pastures as a result of overgrazing and the application of insufficient management decisions, coupled with the detrimental effects of long-term drought, has left extensive areas of high-potential grazing land in southern Africa in urgent need of restoration. However, owing to the limited number of grasses currently available for rehabilitating and restoring the vast number of different habitats encountered, selecting indigenous grasses suitable for restoration of denuded areas in the arid and semiarid grasslands of southern Africa was initiated.

Deforestation in Semihumid and Semiarid Areas

Particularly in the past few decades, it has become evident in many tropical and subtropical countries that deforestation results in the salinization and alkalization of soils due to the effects of soil migration both in the upper and lower layers. In South East India, for example, vast territories of former forest land became intensely saline and sodic (alkaline) in a few years after the annihilation of the woods. Similar phenomena occurred in, for example, the forest steppe areas in Russia, Iran, East-Central Europe, and Latin America.

Salinization Caused by Contamination with Chemicals

In spite of the fact that the amount of chemicals applied in agriculture is practically negligible in comparison with the salt content of several soils, we have considered the fact that this kind of salinization more and more often occurs in modern intensive agricultural production, particularly in greenhouses and intensive farming systems. When production takes place in semiclosed systems (e.g., greenhouses), where the chemicals applied will not be removed regularly, the accumulation of salts or their components becomes possible in the upper layer of the soil, resulting in salinity and sodicity (alkalinity). In Japan, the Netherlands, and other countries with intensive agriculture, and particularly horticulture, such types of salinization more and more frequently appear, causing serious losses of crop yields.

Accumulation of Airborne or Waterborne Salts

Owing to the concentration of industrial plants, the emission of chemical compounds may accumulate in the soil and, if their concentration is high enough, they result in salt accumulation in the upper layer of the soil.

A similar phenomenon appears when, owing to water system regulations, sludge water disposal, and other hydrotechnical measures, water with considerable salt concentration contaminates the upper soil layer, causing salinization and/or alkalization.

RECLAMATION OF SALT-AFFECTED SOILS

Population growth and increasing demand for food and agricultural products necessitate using the salt-affected soils and marginal lands for food production. These soils are needed for the agricultural extension, and hence reclamation is required.

Reclamation is needed on the millions of hectares of slowly permeable salt-affected (i.e., saline-sodic and sodic) soils throughout the world [44].

Different techniques have been used for reclamation of salt-affected soils. Saline soils are usually reclaimed by leaching the salts out of the soil through irrigation and drainage systems. Whereas, reclamation of sodic (alkaline) soils requires application of chemical amendments followed by the leaching process.

Present recommendations for reclamation of the salt-affected soils are usually based only on relatively simple and often empirical relations. Various amendments and management strategies have been used for reclamation of the salt-affected soils. To evaluate particular reclamation strategies, some specific considerations should be noted as follows:

1. Quantity of water needed
2. Quality of water needed
3. Quantity of amendments to be used
4. Type(s) of amendment(s) to be used
5. Time required for reclamation to be completed

Chemical reactions such as cation exchange, precipitation, and dissolution of solid phases (reclamation amendments) and the soil hydraulic properties and corresponding changes in the water flow and solute transport rates must be considered [31].

Among the various reclamation practices, a combination of added gypsum amendment and crop rotation usually has been proven to be the best.

Since reclamation of salt-affected (saline-sodic and sodic) soils by chemical amendments has become cost effective and requires high capital investment, cultivation of salinity and sodicity-tolerant plants ‘‘saline agriculture’’ may be another alternative.

Cultivation of different salinity and sodicity-tolerant plant types and species has been used by several investigators (i.e., grasses [7,25,43], agronomic crops [45], forest species [38,46–48]) for reclamation purposes. These plants can mobilize the native lime (calcium carbonate, $CaCO_3$) in these soils through root action, a substitute for the chemical approach. Qadir et al. [7], studying the combination of chemical amendments and biological (using plants) reclamation technique, reported that the soil treated with gypsum at a high rate (100% GR) removed the greatest amount of Na^+ from the soil columns and resulted in a marked decrease in soil salinity (EC, electrical conductivity) and sodicity, sodium absorption ratio (SAR). The performance of grass treatment in enhancing the leaching of Na^+ was between the gypsum treatments.

According to Kumar [25], the grass *Leptochloa fusca* is very useful and effective in the reclamation of salt-affected soils. This plant can tolerate extremely saline and sodic (alkaline) conditions. Since its growth is not affected by gypsum application, planting with *Leptochloa* is an alternative biological rather than a chemical method for the reclamation of sodic (alkaline) soils. This plant is also well adapted to the waterlogging encountered on saline and sodic (alkaline) soils. The plant improves the soil physical, chemical, and biological properties so that within 2 or 3 years many commercial and forage crops can be grown on the soil [25]. *Leptochloa* excretes salts through specialized glands and is, therefore, reasonably palatable to farm animals. It must be noted that because of its vigorous growth on sodic (alkaline) soils, *Leptochloa* does not allow satisfactory growth of companion plant species, especially in the initial years of soil reclamation.

Subramaniam and Babu [48] also used a forest shrub species for reclamation of sodic soils. According to these investigators [48], *Sophora mollis*, which grows as a shrub to a medium-sized tree and is used for both fodder and firewood, can be used in the reclamation of sodic (alkaline) soils.

Although slow but definite improvement is achieved in the physicochemical properties of the salt-affected soils by encouraging the vegetation growth on such lands. The tree species in general are effective in improving the soil properties as reflected by the changes in physicochemical characteristics of the soil such as bulk density (BD), water-holding capacity (WHC), hydraulic conductivity (HC), and pH, EC, OC (organic carbon), N (nitrogen), and exchangeable cations (Na^+ and Ca^{2+}) [46].

Owing to the low biological activity and depressed microbial growth of salt-affected (i.e., saline, saline-sodic, and sodic) soils, there is a need for applying organic amendments (i.e., plant residue or manure) during sodic (alkali) soil reclamation. In reclamation of saline soils, organic amendments must be applied following the leaching process.

Kumar et al. [35] conducted a combination of biological and chemical reclamation studies on a highly sodic (alkaline) soil. These investigators [35] found that rice produced satisfactory yields in the first year of gypsum application, but sorghum and *Sesbania* yields were very poor. The yield of *Leptochloa* was not affected by gypsum application. In their crop rotation practice, Kumar et al. [35] reported that the green forage yield of sorghum was greatest when sorghum followed *Leptochloa* grown for 2 years and the harvested grass was left to be decomposed on the site.

In a biological reclamation study of saline soils, Helalia et al. [49] reported that amshot grass significantly reduced the soil salinity compared with either ponding or gypsum application, and this grass produced a higher fresh yield than clover cultivated in such soils.

The above findings indicate that biological reclamation with the salinity- or sodicity-tolerant plants (i.e., *Leptochloa*, grasses, shrubs, or trees) is a proper substitute for chemical reclamation with gypsum, and the former has an economic advantage over the latter.

Compost or any other organic materials is recommended to be used during the reclamation process of the salt-affected soils. The results of a field experiment conducted by Avnimelech et al. [24] verified that compost application improved both physical and chemical conditions of saline and sodic (alkaline) soils. Compost application to such soils is expected to release acids which would ultimately lead to the replacement of exchangeable sodium by calcium. In addition, compost application would stabilize soil structure and enhance plant growth. These investigators [24] found that the municipal solid-waste compost application was equivalent or even superior to the addition of gypsum, the most common amendment used to reclaim sodic (alkaline) soils. This was evident from the substantial increase in crop yields. The combined application of compost and gypsum raised yields to the levels equal to that of the commercial fields.

In a field experiment, Batra et al. [30] compared the microbiological and chemical amelioration of a highly deteriorated sodic (alkaline) soil using two reclamation technologies:

1. Growing Karnal grass (*Leptochloa fusca*) as a first crop with no chemical amendment (biological reclamation)
2. Gypsum application as a chemical amendment for different crop rotations

These investigators [30] reported that the microbiological properties changed more than the chemical properties of sodic (alkali) soil as the time period advanced.

In a biological reclamation study carried out on saline soils, Apte and Thomas [50] found that a brackish water, nitrogen-fixing cyanobacterium, *Anabaena torulosa*, could successfully grow and fix nitrogen on moderately saline soils (EC of 5.0–8.50 dS m^{-1}). These investigators [50] reported that cyanobacterium exhibited high rates of nitrogen fixation and substantially enriched the nitrogen status of saline soils. However, permanent removal of Na^+ from saline soils using cyanobacteria or any other microorganisms may not be possible, since Na^+ is released back into the soil subsequent to the death and decay of cyanobacteria or other microorganisms. Amelioration of soil salinity by simultaneous application of *Anabaena torulosa* during crop growth seems to be an attractive possibility for reclamation, especially since it can also supplement the nitrogen requirement of the crops growing on these soils.

Blue-green algae that tolerate excess Na and grow extensively on the soil surface in wet seasons was found to be effective in sodic soils reclamation [51]. However, a permanent reclamation of such soils by using only blue-green algae as a biological amendment to achieve sodic (alkali) soil reclamation is neither possible nor comparable with an effective chemical amendment such as gypsum.

In the reclamation process of the saline soils, De Villiers et al. [33] compared different annual and perennial species. Of the six species tested, the perennials seemed to be more effective and better suited for rehabilitation purposes under saline soil conditions.

The type of chemical compound being used also influences the reclamation process of salt-affected soils. Sharma and Upadhyay [52] reported that, among the up-to-date known chemical compounds, cyclohexathiazenium chloride (S-6N-4)-2+Cl-2 is the best and the most suitable chemical to reclaim the sodic (alkaline) soil at any pH of the soil.

When good-quality water is not available for leaching the salts out of the soil, low-quality water can be used for the initial stages of reclamation. In this regard, Singh and Bajwa [53] studied the effects of gypsum and sodic irrigation on the precipitations of Ca^{2+} and removal of Na^{+} from a sodic soil reclaimed with different levels of gypsum and growth of rice in a greenhouse experiment. Dubey and Mondal [22] also used low-quality saline water in conjunction with organic and inorganic amendments for the initial stages of reclamation of sodic soils. Using low-quality water, Joshi and Dhir [54] evaluated the rehabilitation of degraded sodic soils using residual sodium carbonate water (low-quality water) combined with gypsum treatment and found that the combination treatment was effective in lowering the soil SAR and improved the water infiltration rate. In the first year of gypsum treatment, it was possible to establish the crop. In the second year, a moderate production of wheat (2610 kg ha^{-1}) and raga (*Brassica* sp) (2000 kg ha^{-1}) was obtained [54].

Using the most common technique, irrigation water and drainage system, for reclamation of the salt-affected soils, the results of an investigation carried out by Millette et al. [23] demonstrated the ability of fall irrigation to leach salts from the surface soil during a period of low consumptive use, which could lead to reclamation. Long-term monitoring would be required to determine whether a further and permanent decline in salinity could be achieved.

Concerning other reclamation materials and techniques, results of Jones et al. [55] indicate that acid whey is effective in reclaiming sodic soil by lowering ESP (exchangeable sodium percentage), SAR, and pH and by improving the infiltration rate. Rao and Leeds Harrison [56] used simulation models for desalinization of a drained two-layered saline soil using surface irrigation for different water management practices to increase leaching efficiency. Based on image elements and their correlation with the ground features, Rao et al. [57] suggested categorizing sodic soils in moderately and strongly sodic groups. The delineation thus made would help the execution of a reclamation program for sodic soils at the study sites. Abdel-Hamid et al. [58] monitored soil salinity in the northern Nile delta of Egypt by using data collected via landsat and the geographical information system (GIS). The collected data were used in making recommendations for reclamation of the saline soils of the Nile delta area.

The vast areas of salt-affected soils still remain a burden for the affected societies, particularly the developing countries, where the adequate resources needed to reclaim them with the available technology involve initial heavy investments. The process of degradation, which has been due to reckless destruction of vegetation, can be reversed by reestablishment of vegetative cover which results in slow but definite improvement in such soils. This phenomenon has been very much demonstrated by various parameters influencing the soil welfare in several investigations which show a positive sign of improvement both in terms of physical and chemical properties of the salt-affected soils. Such soils should, therefore, be brought under any type of vegetation (i.e., sod, shrub, tree) cover, if not found to be economical for regular farming and growing agronomic crops [46].

Even by the execution of the reclamation processes, nutrient status and their behavior in salt-affected soils (i.e., saline-sodic and sodic) during reclamation by crop rotation and chemical amendments requires a comprehensive assessment. This is usually because some soil nutrients are also lost and leached out of the soil during the leaching process of the soluble salts and the exchangeable sodium. In this regard, several investigators [8,9,36–38] have studied nutrient status and behavior during the reclamation processes. Swarup et al. [36] reported the effect of gypsum on the behavior of soil phosphorus during the reclamation of a sodic soil. According to Bhojvaid et al. [38], soil nutrient status under the tree plantation was higher than that of the nonsodic farm soil. This finding confirms that successful tree plantation may restore the productivity and fertility of highly degraded sodic soils.

Regardless of the techniques used in reclamation of salt-affected soils, postreclamation management practices, that is, proper choice of crops, crop rotation, method of irrigation, quality and quantity of water used for irrigation and reclamation, fertilization, and the economics of reclamation, must be taken into consideration and followed to achieve successful results.

CONCLUSIONS

In this chapter, information has been given on the important functions of the soil in relation to soil-originated stress factors for plant and crop development as well as a little more detailed information of particular problems related to salt-affected soils and their formation and reclamation.

The properties of the stress factors for plant and crop growth originating in soil are diverse and many sided. We know comparatively little about the status of salt-affected soils and, particularly, for finding methods to improve the situation of reclaiming these soils (salt-affected soils) and ensure better plant and crop development. Therefore, target-oriented studies of the different kinds of soil-originated stress factors for plant and crop growth are necessary so that the complex correlations and the actions in the soil-plant-water system can be understood for the purpose of a better characterization of stress factors on the one hand and improving the environmental and production conditions on the other hand.

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2

Influence of Sodium on Soils of Humid Regions

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INTRODUCTION

A salt-affected soil is defined as one that has been adversely affected to the extent that it is no longer suitable for the growth of most crops by the presence or action of soluble salts. This group of soils includes both saline and sodic soils. James et al. [1] defined a saline soil as one that contains a quantity of soluble salts sufficient to interfere with the growth of most crops. On the other hand, a sodic soil possesses enough exchangeable sodium (ExNa) also to have an adverse effect on the growth of most plants. A saline-sodic soil contains both soluble and exchangeable Na at levels that impose stress on plant growth.

Salt-affected soils are a common feature of arid and semiarid landscapes. In humid regions, soils may become salt affected when they are irrigated with brackish water or treated sewage effluent, intruded by sea water, or contaminated with oil well brines. Some differences exist between salt-affected soils found in arid and semiarid regions and those found in humid and tropical regions. Sodic soils found in arid and semiarid regions are usually associated with high pH and dominated by the 2:1–type clay minerals. Salt-affected soils in humid or tropical regions generally have low pH, and they are often, but not always, dominated by 1:1–type clay minerals.

The loss of plant productivity from the excess of salinity is a worldwide problem. Where salinity is a problem, an effective use of soil and water resources dictate the production of agricultural crops. Numerous laboratory and field experiments have been conducted in order to determine the plant growth and yield response to various levels of soil salinity. For example, Shalhevet et al. [2] found that the yield of peanuts grown in artificially salinized plots was reduced to 50% at EC_e (EC_e = specific electrical conductance of saturated extract) of 4.7 dS m^{-1} and by 20% at EC_e of 3.8 dS m^{-1}. Additionally, these investigators reported that salt tolerance was much higher during germina-

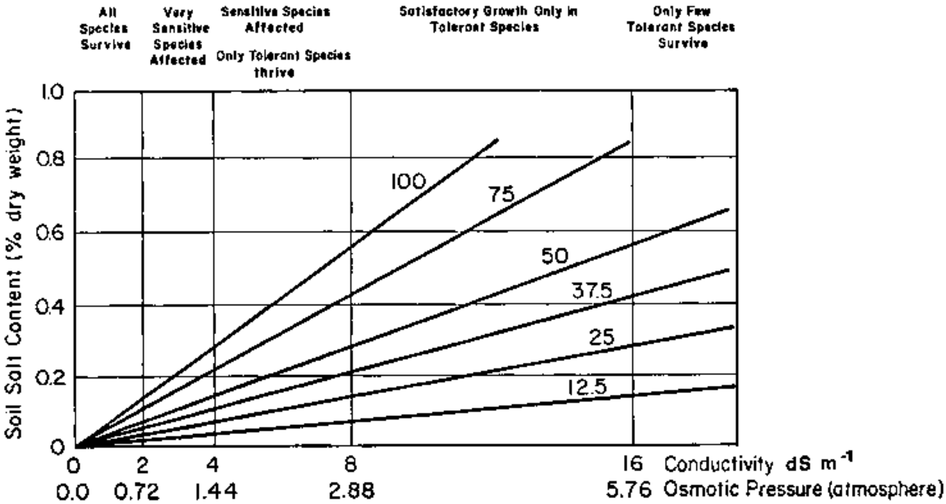

FIGURE 1 Relationship between electrical conductivity (EC) of soil solution and salt content. The numbers in the plot represent grams water needed to saturate 100 g soil. (It takes 12.5 g water to saturate 100 g sand, 100 g water to saturate 100 g clay, and about 50 g water to saturate 100 g of most Kentucky soils.) (From Ref. 6.)

tion than during subsequent growth. A 50% reduction in germination occurred at $EC_e = 13$ dS m^{-1}. Shalhevet and Yaron [3] reported a 10% yield reduction in tomatoes for every 1.5 dS^{-1} increase in EC_e above 2 dS m^{-1}. The adverse effects of soil salinity on plant growth and productivity vary with the type of plant being grown. A summary of the general response of plants to salinity is presented in Figure 1.

The presence of salinity in the soil solution resulting from either indigenous salt or that through irrigation can affect plant growth in three ways: (a) It can increase the osmotic potential and hence decrease water potential, thereby reducing water availability, the *osmotic effect*. (b) It can increase the concentration of certain ions that have an inhibitory effect on plant metabolism, a process known as the *specific-ion effect* [1]. (c) It can adversely affect soil structure such that water permeability and soil aeration are diminished [4], the *physicochemical effect*.

Osmotic Effect

The osmotic effect on plant growth is related to water availability or soil-water potential. Under normal field conditions, the soil-water potential, U_w, is determined by the osmotic potential, U_s, the matrix potential, U_m, and the gravitational potential, U_p. Mathematically, U_w is described by the equation

$$U_w = U_m + U_s + U_p \tag{1}$$

At any given matrix potential and a fixed gravitational potential, an increase in salinity is manifested by a reduction in U_w [1]. Bresler et al. [5] pointed out that physicochemically it can be shown that U_s of a solution is directly related to total dissolved solids (TDS). The relationship between U_s and TDS can be expressed by the following equation [6]:

$$U_s \text{ (bar)} = -5.6 \times 10^{-4} \times \text{TDS (ppm)} \tag{2}$$