AMELIORATION OF ALKALI (SODA-SALINE) SOILS

Pankova Ye.I.
V.V. Dokuchaev Soil Science Institute, Moscow, Russia

Redly M.
Research Institute of Soil Science and Agricultural Chemistry, the Hungarian Academy of Sciences, Budapest, Hungary

Aidarov I.P. and **Pestov L.F.**
Moscow State University of Environmental Engineering, Moscow, Russia

Keywords: sodium, soda, neutralization, chemical amelioration, amendment requirements, calcium chloride, sulfuric acid, gypsum, phosphogypsum, ferrous sulfate, coagulation of soil colloids, loosening, leaching requirements, degree of salinity, meliorant crops

Contents

Summary

Data on the diagnostics and quality assessment of alkali (soda-saline) soils are outlined. The properties limiting the fertility of these soils and the means of their amelioration are considered. The methods of calculating the optimum requirements of chemical amendments and leaching required to remove toxic salts (including those that appear in the soils after their treatment with an amendment) are described. The peculiarities of amelioration of soda-saline soils in conditions of irrigation and dry farming are discussed. Examples of successful management of reclaimed soda-saline soils are given.

1. Introduction: Diagnostics and Main Properties Limiting the Fertility of Soda-Saline Soils

1.1. Definition and Diagnostic Criteria

Soda-saline soils represent a subgroup of alkali soils distinguished by the presence of sodium carbonates (Na_2CO_3 and $NaHCO_3$) in the soil solution in amounts that hamper the development of crops and exert a negative effect on the soil quality. Some other soluble salts (chlorides and sulfates of sodium and magnesium) may also be present, but the dominant role in forming adverse soil properties and conditions for plant development is played by sodium carbonate. Unlike the subgroup of sodic (solonetzic) alkali soils, soda-saline soils, especially those with a high content of salts, do not have a morphologically distinct solonetzic (natric) horizon.

According to I. Szabolcs, soda-saline soils can be categorized as a subgroup of alkali soils without a natric horizon (subsurface clay-illuvial horizon with columnar or columnar-prismatic structure and having ESP > 15). Thus, the presence or absence of a morphologically distinct natric horizon serves as the basis for the division of alkali soils into two subgroups that require different amelioration measures. The main factors limiting the fertility of sodic (solonetzic) soils are their poor water-physical and agrophysical properties. The fertility of soda-saline soils is limited by their chemical and physico-chemical properties, which are affected by the presence of sodium carbonate in the soil solution. These soils are strongly alkaline (pH 9–11), which entails the absence of calcium in the soil solution. Hence, the exchange complex of soils is saturated with exchangeable sodium.

The exchangeable sodium percentage (ESP) in soda-saline soils reaches 40–80% of the cation exchange capacity (CEC). The prevalence of exchangeable sodium in the exchange complex causes clay peptization, degradation of soil aggregates, a decrease in the water conductivity, very high bulk density of soils (compactness) when dry, and their oversaturation with water when wet. Thus, in addition to strong alkalinity, soda-saline soils are characterized by the adverse water-physical properties typical of sodic (solonetzic) soils. If the topsoil horizon of soda-saline soils contains more than 0.5–0.7% of Na_2CO_3 and $NaHCO_3$, determined in a 1:5 soil-water extract, and has an electrical conductivity (ECe) value of higher than 8–16 dS m^{-1}, then this soil can be distinguished as a soda-affected solonchak–solonetz, characterized by the presence of morphologically distinct solonetzic (natric) horizon on the background of soda salinization.

The high alkalinity of soda-saline soils adversely affects most of crops and soil biota. Alkaline conditions lead to the disturbance of metabolic processes in plants and disrupt the nutrient balance. In particular, the availability of calcium, magnesium, phosphorus, iron, manganese, and several other essential nutrients considerably decreases. Soda (sodium carbonate) is considered the most toxic of all the soluble salts found in natural soils. According to *Soil Taxonomy* and many national classifications, soda-saline soils are diagnosed on the basis of a combination of two analytical indices: the ECe and the ESP. If the soil has an ECe greater than 4 dS m^{-1} and ESP above 15%, it can be referred to as an alkali soda-saline soil.

Along with ECe and ESP, the sodium adsorption ratio (SAR) is often used for diagnostic purposes. The SAR value allows one to estimate the probability of the appearance of exchangeable sodium in the exchange complex, and, hence, to predict the development of solonetzic processes in the soil. The SAR value is correlated with ESP. The residual sodium carbonate (RSC) content is also used to characterize soda-saline soils. The RSC value is calculated by subtracting the sum of exchangeable calcium and magnesium from the total alkalinity (the concentration of HCO_3^- ions in the water extract) of the soil, expressed in cmol kg^{-1}.

In Russia and several other countries, the study of water extracts (with a soil-to-water ratio of 1:5) is used to characterize the degree of soil salinity. Soda-saline soils are distinguished in the classification of salt-affected soils accepted in these countries according to the following criteria:

HCO_3^- >0.8–1.0 cmol kg^{-1}
$pH_{(1:2.5)}$ >8.5, and
HCO_3^- > $Ca^{2+} + Mg^{2+}$

The sum of toxic soluble salts in the root zone is also taken into account to classify soda-saline soils (as well as other salt-affected soils) by their degree of salinity (Table 1).

Degree of soil salinity	**Soil salinity index in relation to the composition of salts**							
	predominantly chlorides			**Predominantly sulfates (including the chloride–sulfate type of soil salinity)**		**predominantly sodium carbonate/ hydrocarbonate**		
	S_{tox}**	**Cl^-**	**Na^+**	**S_{tox}****	**Na^+**	**S_{tox}****	**HCO_3^-**	**Na^+**
	%	**cmol kg^{-1} soil**		**%**	**Cmol kg^{-1} soil**	**%**	**cmol kg^{-1} soil**	
Non saline	<0.05	<0.3	<0.6	<0.15	<1	<0.1	<0.8	<0.6
Slightly saline	0.05–0.12	0.3–1	0.6–2	0.15–0.30	1–2	0.1–0.15	0.8–1.4	0.6–2
Moderately saline	0.12–0.35	1–3	2–4	0.3–0.6	2–6	0.15–0.30	1.4–2.0	2–4
Strongly saline	0.35–0.70	3–7	4–8	0.60–1.0	6–12	0.30–0.60	2.0–3.0	4–8
Very strongly saline	>0,7	>7	>8	>1	>12	>0.60	>3.0	>8

* The degree of soil salinity can be estimated by any of the indices given in this table
** The sum of toxic salts (S_{tox}, %) is equal to the sum of toxic ions expressed as a percentage of the soil mass. Cl, Na, and Mg ions are considered toxic ions; $HCO_{3(tox)} = HCO_{3(total)} - Ca$ ($mmol_c.kg^{-1}$ soil (2x)); $SO_{4(tox)} = SO_{4(total)} - (Ca–HCO_3)$, meq 100 g^{-1} soil. $S_{tox} = HCO_{3(tox)} + Cl + SO_{4(tox)} + Na + Mg + K$, %.

Table 1. Assessment of soil salinity by the sum of toxic salts and the content of separate ions*

Along with purely soda-saline soils, soda-chloride and soda-sulfate saline soils are distinguished. Soda-saline soils, as well as other salt-affected soils, can be subclassified according to the depth of the saline horizon and the presence (or absence) of calcium carbonates in the soil profile. All these features are of great importance for the choice of proper soil amendments and amelioration methods.

The indices used in the Russian classification of salt-affected soils are also applied in several local (regional) classifications. For example, the group of saline soils includes not only solonchaks and the soils with strongly saline surface horizons (salic soils), but also alkali soda-saline soils that contain a horizon enriched with soluble salts at a depth varying from 0 to 125 cm. The depth of saline horizon is taken into account in establishing subclassifications.

Soda-saline soils can be also subdivided into three groups—hydromorphic, semihydromorphic, and automorphic (mesomorphic) soils—with respect to the depth of the groundwater table. Hydromorphic soda-saline soils are most widespread; groundwater often serves as the source of sodium carbonate in these soils. The groundwater depth is a key parameter to be considered when selecting methods of soil amelioration and determining the sources of sodium carbonate in the soil.

V.A. Kovda revealed the relationship between the properties of soda-saline soils and their relative fertility. His assessment of soda-saline soils was based on three major indices: (a) the total alkalinity in water extracts (1:5) from the soils, (b) the ESP, and (c) pH. At HCO_3^- 0.02–0.04%, ESP 5%, and pH 7.5–8.5, the relative fertility of the soil is estimated as 100%; at HCO_3^- 0.05–0.06%, ESP 10–15%, and pH 8.5–9.0, it decreases to 60–75%; and at HCO_3^- 0.07–0.08%, ESP 10–15%, and pH 9.0–9.5, it is as low as 20–30%. When these values are higher, the soil becomes virtually infertile.

1.2. The Genesis of Soda and Geographic Distribution of Soda-Saline Soils

The origin of soda (Na_2CO_3) in the soils has been thoroughly studied (V.A. Kovda, N.I. Bazilevich, I. Szabolcs, etc.). It is found that soda can appear in the soils owing to different geochemical and soil processes.

(1) The weathering of parent rocks containing sodium aluminosilicates results in the synthesis of soda:

$$Na_2SiO_3 + 2H_2O \rightarrow 2NaOH + 2SiO_3 \quad (1)$$

$$2NaOH + H_2CO_3 \rightarrow Na_2CO_3 + 2H_2O. \quad (2)$$

This process was thoroughly described by B.B. Polynov, using the example of salt-affected soils in Mongolia. Afterwards, Kovda demonstrated the significance of this process in the origin of soda in different regions.

(2) The interaction between calcium carbonate and chloride–sulfate–sodium salts (the Hilgard reaction, 1892):

$$CaCO_3 + Na_2SO_4 \leftrightarrow Na_2CO_3 + CaSO_4; \quad (3)$$

$$Na_2SO_4 + Ca(HCO_3)_2 = 2NaHCO_3 + CaSO_4. \quad (4)$$

(3) The interaction between calcium ions in soil solution with exchangeable sodium (Gedroitz, Sigmond, Kelley).

(4) The biochemical synthesis of soda as a result of the activity of sulfate-reducing microorganisms in anaerobic conditions and in the presence of organic matter and sodium sulfates:

$$Na_2SO_4 + 2C \rightarrow 2CO_3 + Na_2S \quad (5)$$

$$Na_2S + CO_2 + H_2O \rightarrow Na_2CO_3 + H_2S. \quad (6)$$

This particular mechanism of soda formation was found by I.N. Antipov-Karataev on sodium-saline soils in the Russian plain, by A.R. Verner and N.V. Orlovskii in Western Siberia, and by I. Szabolcs in Hungary. The biochemical process of soda formation is typical in marshland soils, bottoms of shallow lakes, sea lagoons, and coastal deltas (Kovda). It is known that the synthesis of soda can also be due to denitrification of nitrogen-bound sodium compounds.

(5) The biogenic process of soda formation is related to the mineralization of the organic matter. Some salt-resistant crops can accumulate considerable amounts of alkaline carbonate salts, which get into the soil in the course of the biological turnover of substances. Kovda emphasized that alkaline carbonates can accumulate in the soil in a form of organic acids, which, interacting with carbonic acid, produce sodium (and potassium) carbonates. According to Kovda, a similar process takes place in deep zones of the Earth's crust, within the areas of oil fields. Usually, deep groundwater in such areas is rich in bicarbonates and carbonates of alkaline elements. In places of groundwater discharge, the soils are affected by soda salinization. Thus, head groundwater may serve as the source of soda in the soils.

A new theory of soda formation in the soils has recently been suggested. It argues that soda can appear upon the selective leaching of ions from surface horizons of salt-affected soils. This phenomenon has been observed in experiments, but has not been proved for natural soils; it is rather a hypothesis than a theory. In general, in spite of a long history of investigation, the problem of the genesis of soda in soils is still an object of interest. It is evident that a range of soil and geochemical processes may be responsible for soda salinization of soils.

Soda-saline soils are widespread in many countries, but their exact extent is still unknown. In FAO–UNESCO data, the area of soda-saline soils is included in the total area of alkali soils. Numerous publications in which the soda-saline soils are described prove their widespread distribution in the United States, India, China, Russia, Armenia, and other countries.

The geography of soda-saline soils shows that they are most often found in particular natural zones: deserts, semideserts, steppes, and forest-steppes. Local areas of these soils are also found in the boreal forest zone. The northernmost area of soda-saline soils is located in the taiga zone of Yakutia, where permafrost-affected soda-saline meadow soils have been described.

These facts indicate that the conditions of formation of soda-saline soils are very diverse. These soils appear in different environments.

The genesis of soda can be related to different processes. Therefore, it is impossible to recommend a uniform amelioration technology that can be efficiently applied to all soda-saline soils. At the same time, the main principles of amelioration measures applied in different regions have much in common, as can be seen from analysis of the literature on it.

2. Amelioration of Soda-Saline Soils

2.1. Theoretical Basis: The Goals of Amelioration of Soda-Saline Soils

The essence of interactions between soil solutions and the exchange complex was experimentally studied and theoretically substantiated in the beginning of the twentieth century (the works of K.K. Gedroitz, A.A. Sigmond, W.P. Kelley, and E.W. Hilgard). There were thorough investigations of the physicochemical properties of saline soils, cation-exchange and cation adsorption processes that govern the genesis and determine the amelioration measures of salt-affected soils.

Later, important contributions to this subject were made by V.A. Kovda, I.N. Antipov-Karataev, E. Bresler with co-authors, D.L. Suarez, and other scientists from different countries. However, the study of physicochemical processes in saline soil still remains relevant today. We need to know in detail the processes that take place in soil upon application of chemical amendments (see *Chemical Amelioration of Soils*).

The goal of amelioration of soda-saline soils, including solonetzic and solonchakous varieties, is to improve their fertility through certain impacts on their physicochemical, agrophysical, and water-physical properties. This can be achieved by using chemical amendments, agrotechnical measures (special soil cultivation procedures), and phytomelioration, in combination with soil leaching to remove salts under natural or, sometimes, artificial drainage.

The aims of chemical amelioration of soda-saline soils are to neutralize soil alkalinity and to replace exchangeable sodium and magnesium in the soil exchange complex by calcium. Calcium adsorption by the exchange complex enhances the coagulation of soil colloids and improves the water-physical state of soils, which is necessary for the successful leaching of water-soluble salts from the root zone.

The application of various soil amendments is expensive when a moderate or strong degree of salinity is observed in the upper 100 cm depth of the soil. In conditions of a shallow groundwater table and poor natural drainage of the territory, artificial drainage systems are required.

In order to improve the fertility of chemically reclaimed soils and to eliminate the residual solonetzic properties of the soils, organic fertilizers (manure, composts, green manure crops) should be applied and special soil-improving (meliorant) crops should be grown.

-
-
-

Bibliography

Abrol I.P., Yadav J.S.P., and Massound F. (1988). *Salt Affected Soils and Their Management*, 131 pp. FAO Soils Bulletin 39. Rome: FAO. [This monograph provides extensive data on salt-affected soils, including soda-saline soils, and the methods of their management and reclamation.]

Agababyan V.G. (1993). *Amelioration of Soda-Saline Solonchak–Solonetzes by Sulfuric Acid*, 184 pp. Moscow: Technological Center of Russia. [The results of experimental works on the reclamation of soda-saline soils in Armenia are outlined.] [In Russian.]

Aver'yanov S.F. (1978). *Salinization Control on Irrigated Lands*, 288 pp. Moscow: Kolos. [This work elucidates theoretical backgrounds of the regulation of water and salt regimes of irrigated soils.] [In Russian.]

Bresler E., McNeal B.L., and Carter D.L. (1982). *Saline and Sodic Soils*, 236 pp. Berlin, Heidelberg, New York: Springler-Verlag. [This monograph is devoted to quantitative descriptions of water- and salt-transfer processes in solonetzes and solonchaks, especially under irrigation.]

Kovda V.A. (1963). *Alkaline Soda-Saline Soils*, 28 pp. Paris: UNESCO. [This is a concise review of the problems of genesis, geography, and reclamation of soda-saline soils.]

Kovda V.A. (ed.) (1971). *Soda-Saline Soils and Their Reclamation*, 771 pp. *Proceedings of the International Symposium on Reclamation of Soda-Saline Soils*, (26–31 May, 1969) Yerevan, USSR: Acad. Sci. Armenian SSR. [This monograph contains data on soda-saline soils and their reclamation in different countries.] [In Russian.]

Richard L.A. (ed.) (1954). *Diagnosis and Improvement of Saline and Alkali Soils*, 160 pp. USDA Handbook no. 60. Washington DC: US Department of Agriculture. [The diagnostic and quality assessment criteria of salt-affected soils are described.]

Summer M.E. and Naidu R. (eds.) (1998). *Sodic Soil: Distribution, Properties, Management and Environmental Condition*. 207 pp. Oxford, U.K.: Oxford University Press. [The monograph contains data on the geography, properties, and reclamation of sodic and solonetzic soils.]

Szabolcs I. (1996). Global overview of sustainable management of salt affected soils. *Proceedings of the International Workshop on Integrated Soil Management for Sustainable Use of Salt Affected Soils.* BSWM. Diliman Quezon City, Manila, Philippines, 6–10 November 1995, (ed. A. T. Ayoub (UNEP), A. M. Mashali (FAO), M. Redly (ISS)). pp. 19-38. 237 pp. Budapest, Hungary.

Szabolcs I. (1989). *Salt Affected Soils*, 274 pp. Boca Ration, Fl: CRC. [This is a general review of current data on the distribution, genesis, properties, and classification of saline and solonetzic soils. The problems of their management are also considered.]

Tanji K.K. (ed.) (1990). *Agricultural Salinity Assessment and Management*, 619 pp. ASCE Manuals and Reports on Engineering Practice, No. 71. , New York: American Society of Civil Engineers. [This manual integrates contemporary concepts and management practices for agricultural water and salinity problems.]

Biographical Sketches

Yevgenia Ivanovna Pankova was born in 1932. In 1955, she graduated from the Geographical Department, Moscow State University, with a diploma in soil geography and environmental geochemistry. Since then, her scientific career has been connected with the Dokuchaev Soil Science Institute. At present, she is the leading researcher of the Department of the Genesis and Amelioration of Salt-Affected Soils, Doctor of Agricultural Sciences, and a corresponding member of the Russian Ecological Academy. She is the author of more than 200 works, including five monographs, devoted to the genesis, mapping, and monitoring of salt-affected soils.

Marianna Redly is senior soil scientist at the Research Institute of Soil Science and Agricultural Chemistry of the Hungarian Academy of Sciences. Budapest, Hungary. She was born in 1933. Her academic background is physical and colloid chemistry. She defended her doctor's theses from the cation exchange properties of alkali soils. She is the author of about 40 papers on the laboratory methods of determining the diagnostic parameters of saline and alkali soils, and on the description and modeling of physico-chemical processes in alkali soils. She acted between 1986-1994, as vice chairperson, and between 1994-1998, as the chairperson of the Subcommission of Salt Affected Soils of the International Soil Science Society.

Ivan Petrovich Aidarov was born in 1932. In 1955, he graduated from the Moscow Institute of Hydraulic Engineering and Water Management with a diploma as a specialist in hydromelioration. At present, he is a pro-rector of the Moscow University of Environmental Management. He is a Doctor of Technological Sciences, Professor, and an Academician of the Russian Agricultural Academy. His major works are devoted to amelioration of salt-affected soils and ecological problems of ameliorated lands.

L.F. Pestov was born in 1932. In 1955, he graduated from the Moscow Institute of Hydraulic Engineering and Water Management with a diploma as a specialist in hydromelioration. In 1973, he defended his Candidate theses. He is a senior researcher at the Moscow University of Environmental Management, specializing in amelioration of agricultural lands, salinization control, and drainage construction.