AMELIORATION OF ALKALI (SODIC/SOLONETZ) SOILS

Lyubimova I.N. and Pankova Ye.I.
V.V. Dokuchaev Soil Science Institute, Russia

Pestov L.F.
Moscow State University of Environment Management, Russia

Keywords: alkali soil, salinization, sodium, peptizeable clay, amelioration, chemical amendment, gypsum, phosphogypsum, sulfuric acid, amendment requirement, plantage, three-stage plowing, rotary tillage, deep loosening, phytomelioration, complex amelioration, water accumulation measures, agricultural afforestation.

Contents

Summary

This article synthesizes available information about the genesis and distribution of alkali soils, and criteria for their diagnosis and classification. The properties that restrict soil fertility and measures to ameliorate them are described in detail. The amendments commonly applied (gypsum, phosphogypsum, sulfuric acid), kinds of ameliorative treatments, and a set of crops suitable for phytomelioration, as well as methods to calculate amendment requirements and the thickness of calcareous horizon to be plowed are presented. An ecological assessment of reclamative practices is given. Special attention is paid to a system of water accumulation and irrigation practices to control the moisture regime in soils under reclamation. Examples are cited to show the effectiveness of different practices for amelioration of alkali soils in Bulgaria, Hungary, Canada, India, Kazakhstan, Russia, Romania, and the United States.

1. Diagnosis of Alkali Soils: Concept, Indices and Criteria for Evaluation

Alkali or sodic soils (solonetzes) are those with a texture-differentiated profile of an eluvial-illuvial type. Within the upper (0–50 cm) soil layer the natric or solonetzic horizon can be distinguished, whose formation is associated with Na-rich clay lessivage. The presence of sodium salts appears to be a determining factor for the development of these soils. These salts may be inherited from the parent material, enter the soil with ground, surface, or irrigation water, or with eolian dust, or they may be formed by biogenic accumulation. Alkali soils may be formed by the desalinization of soils that were initially salinized largely with sodium salts, or through the alteration of salinization/desalinization processes. This process takes place most actively in conditions of sodium carbonate salinity (soda-saline soils). In soils under irrigation the occurrence of alkalinity may be associated with the quality of irrigation water, because a high percentage of sodium in the water and a salt composition dominated by sodium carbonate can lead to soil alkalinity even at a low mineralization.

The presence of exchangeable sodium in the soil adsorption complex (SAC) when the water-soluble salts are virtually absent determines the specific properties of the solonetzic horizon. The latter shows an alkaline reaction (high pH), due to the hydrolysis of exchangeable sodium and soda and the appearance of sodium carbonate in the soil solution. This is caused by the replacement of sodium by calcium and the dissolution of $CaCO_3$ into sodium carbonate solutions (soda alkali soil). The natric/solonetzic horizon is characterized by a highly dispersed soil mineral part, high mobility of organic matter and peptizeable colloids, tensile strength, stickiness, and swelling when wet, and compaction or even hardness in dry conditions. Alkali soils have a low water permeability and weakly pronounced physiological water availability. The specific structure of the solonetzic horizon is columnar-blocky or prismatic-columnar under dry conditions. The peds are usually covered by brownish-black or cinnamonic clayey-organic films, with pale gray silica powder on the top of columnar peds. Over the natric/solonetzic B horizon, a whitish-grey humus-eluvial A horizon can be found, which is impoverished in clay particles; its thickness varies from 1 or 2 cm to 20–30 cm. The humus content ranges from 1% in semidesert areas to 6–9% in the soils of forest steppes and steppes. Under the solonetzic horizon, calcareous, gypsiferous, and salt-containing horizons can be found as transitions to the frequently salt-affected parent material. The content, thickness, and depth of these horizons vary depending on local conditions.

The natric/solonetzic horizon is usually used as the main diagnostic (reference) horizon in the classification of alkali soils in different soil classification systems: the American Soil Taxonomy, French soil classification (CPCS), the classification and diagnostics of soils in the former USSR, and so on. Qualitative–quantitative criteria have been proposed to distinguish the natric/solonetzic horizon: minimum thickness (15 cm); the increased content of the clay fraction as compared with the overlying horizon, showing evidence of the clay lessivage; the presence of optically oriented clays on peds; and the columnar-blocky structure of the horizon. In the Soil Taxonomy, the physico-chemical indices of alkali (sodic/solonetz) soils are determined according to whether:

- the exchangeable sodium percentage (ESP) of the solonetzic horizon is over15%,

- the sodium absorption ratio (SAR) value is over 13%,
- ratio of exchangeable cations (Mg + Na > Ca + H) 4) pH > 8.5, and
- EC_e, 4 dS m^{-1} (though this threshold value varies for different soil classes).

These indices have been widely adopted for the diagnosis of alkali (sodic/solonetzic) soils in many countries all over the world. It is found that ESP = 10–15% is a threshold value; at higher levels the features characterizing alkali soils become apparent (swelling, clay dispersal, impoverishment of agrochemical value of the soil structure, etc.). However, ESP threshold values causing unfavorable soil properties can vary depending on the mineral composition of clay and other indices. Solonetz-like soils can be identified as those with ESP value of 3–5%.

The pH value of alkali soils ranges from 8.5 to 10.5. This high soil pH value is determined by the presence of sodium carbonate in the pore solutions. Once the SAR value in a soil saturation sample or in irrigation water has been determined, it is possible to estimate the risk of soil alkalinity/sodicity resulting from changes in the composition of irrigation water in soils due to precipitation or dissolution of Ca salts.

EC_e is the electrical conductivity of saturated extract at 25 °C measured in dS m^{-1}.This measurement makes it possible to distinguish saline and non-saline soils. The threshold value is $EC_e > 4$ dS m^{-1}. The characteristics of EC_e and ESP permit us to classify soils according to the degree of their salinity and alkalinity:

1.	saline	$EC_e > 4$ dS m^{-1}; ESP < 15
2.	saline alkaline	$EC_e > 4$ dS m^{-1}; ESP > 15
3.	alkaline	$EC_e < 4$ dS m^{-1}; ESP > 15
4.	non-saline non-alkaline	$EC_e < 4$ dS m^{-1}; ESP < 15

Thus we can identify soils as non-saline alkaline (group 3), and saline alkaline (group 2), which are frequently referred to the group of solonetz-solonchaks.

In Russia and in some other countries, water extract from soil (with a soil-to-water ratio of 1:5) is used to characterize soil salinity. The latter is assessed by the sum of toxic salts or by the concentration of separate ions (Na^+, Cl^-, HCO_3^-). See *Chemical Amelioration of Soils* (Table 4) and *Amelioration of Soda-Saline Soils* (Table). The degree of soil solonetzicity ids assessed by soil morphology and by the exchangeable sodium percentage (ESP) in the subsurface clay-illuvial horizon.

Different classifications of alkali soils are accepted in various countries, including Canada, France, and the United States. A detailed classification of these soils has been elaborated in Russia and the in the other republics of the Former Soviet Union. Various factors are involved.

In the soil classification accepted in Russia, alkali soils (solonetzes) are classified according to the groundwater table (GWT) and the moisture regime: automorphic (GWT > 6 m), half-hydromorphic (GWT from 6 to 3 m), and hydromorphic (GWT < 3 m) solonetzes are identified. The groundwater table determines the moisture and the salt regimes of soil. In *hydromorphic solonetzes,* due to their exudational moisture regime, the salts accumulate in the upper soil horizons. In rainy periods the salts are leached down the profile to some extent. The alternation of water flows under dry and wet conditions leads to periodical salinization and desalinization of the soil, thus activating the process of alkalization. In *half-hydromorphic solonetzes* the water–salt regime is desuctive-exudational. The film-capillary water is discharged for transpiration from the root layer, concentrating the salt at that level. In *automorphic* non-irrigated soils the ground water has no effect upon the soil. Salt distribution throughout the soil profile depends on the depth of moistening by precipitation. Under irrigation the water–salt processes are governed by the percolative moisture regime.

Meliorative properties of solonetzes are determined by specific features of the natric/solonetzic horizon, namely by the content of exchangeable sodium, and the agrophysical and physico-chemical properties of soils. Depending on the content of exchangeable sodium, the solonetzes can be classified into: residual-sodium (ESP < 10%), poor in sodium (ESP 10–25%), moderate in sodium (ESP 25–40%), and rich in sodium (ESP > 40%). In solonetzes poor in sodium, the agrophysical properties are considered to the limiting factors of soil fertility, while in soils rich in sodium, fertility is limited by the soil's physico-chemical properties. Chemical amelioration is the main management practice for solonetzes rich in sodium.

The characteristics of salinity in solonetzes are based upon the same indices used for saline non-alkali soils. Alkali soils (solonetzes) are also distinguished according to the upper boundary of the salt-bearing horizon, the salt composition, and the degree of salinity. *Surface-alkali* soils are those whose salt horizon can be found within 0–30 cm of the surface; *alkali soils* have salt horizon in the middle (30–80 cm) depth of the profile; in the *deep alkali soils*, the salt horizon can be found at 80 cm or deeper. The depth of the salt occurrence is a criterion for the choice of soil-improving measures and the kinds of meliorative soil tillage. The latter should not entail accumulation of salt in the plow layer. For instance, it is irrational to cultivate surface-alkali soils without preliminary salt leaching from the soil.

Depending on the salt composition dominating in the soil profile, we can distinguish:

- Solonetzes salinized by neutral salts (chlorides and sulfates). Increased alkalinity—pH > 8.5; and HCO_3 > (Ca + Mg) $mmol_c\ kg^{-1}$—appears only periodically in these soils but their agrophysical properties remain unfavorable, like those of typical solonetzes. Such soils are widespread in Russia, Kazakhstan, Canada, and many other countries. Together with chemical amelioration, tillage practices have proved to be the basic technique of their reclamation.
- Solonetzes salinized by alkali salts (soda: Na_2CO_3, $NaHCO_3$). In these soils the sodium carbonate is constantly present (pH > 9) and they are alkalinized—HCO_3 > (Ca + Mg) $mmol_c\ kg^{-1}$. A complex of chemical amendments in combination with salt leaching is required for reclamation of these soils.

In the classification of solonetzes, the depth of gypsiferous and carbonate horizons along the soil profile is taken into account. From this point of view, the soils are subdivided into high calcareous types, containing carbonate in the 0–45 cm layer, and deep calcareous types where the carbonate occurs below 45 cm. The same distinction is used for determining the content of gypsum in solonetzes. The depth and content of carbonates and gypsum are also taken into consideration for the choice of management practices of soil reclamation.

Solonetzes are also distinguished according to the thickness of the overlying "A" horizon. Crusty and shallow solonetzes are those where the thickness of the A horizon is less than 10 cm. It is very difficult to cultivate these soils, because during plowing the natric/solonetzic horizon can easily be mixed with the plow layer. In moderate solonetzes the thickness of the A horizon is between 10 and 18 cm, and in deep solonetzes it is more than 18 cm. The latter soils are considered to be more productive than the former. The thickness of the A horizon determines the kind of plowing suitable for amelioration of these soils.

Solonetzes are also classified according to the humus content in the overlying and solonetzic horizons, the adsorption (cation exchange) capacity, and many other features depending on natural-climatic conditions of the soil formation.

A great diversity of alkali soils (solonetzes) is evidenced in the legend of the new (FAO/UNESCO) Soil Map of the World (1989). The soils are divided into haplic, gypsic, gleyic, calcic, mollic, and stagnic types.

Alkali soils are widespread in many countries of the world, especially in Australia, in the NIS countries, Argentina, and Canada. In Russia the area occupied by soils of the solonetz complex is estimated as about 300 000 km^2; of these, 230 000 km^2 are used in agriculture, including 100 000 km^2 of cropland. Alkali (sodic/solonetz) soils occur most frequently in steppe, dry steppe, and semidesert zones that periodically suffer from water deficit. The alternation of dry and wet seasons is the obligatory precondition of their formation. These soils are developed to a lesser extent within forest-steppe and desert zones. They are mainly derived from clayey and loamy deposits, although there are instances of their development on light-textured parent materials. However, the parent materials, or ground or surface waters in regions where the alkali soils are formed, invariably contain water-soluble salts, which provide the sodium necessary for alkalinization. Alkali (sodic/solonetz) soils are usually confined to different relief elements and form under various geochemical conditions: in plakors of eluvial landscapes with deep groundwater tables, in transitional and accumulative landscapes, and in accumulation zones of surface and ground water runoff when the groundwater depth is close to the surface.

The variety of conditions for the development of alkali soils, like the diversity of their properties, makes their meliorative cultivation a complex matter. An approach to amelioration of these soils should take into account the specific features of the properties that limit their productivity.

2. Properties Limiting the Productivity of Alkali Soils

Most alkali soils have low natural productivity. Figure 1 shows an alkali soil on cropland without amelioration. In virgin soils it is possible to obtain yields of 5–50 tons of grass for hay per 0.01 km^2. In wet years yields may be similar to those obtained on zonal soils. Agrophysical, physiological, and hydrological properties, along with the complex soil cover pattern, are considered to be limiting factors of the productivity of these soils.

Figure1. An alkali soil on cropland under amelioration.

Agrophysical factors: The main factors limiting the productivity of alkali soils are their water-physical properties. Under wet conditions the soil mass of the natric/solonetzic horizon is thixotropic, being in a colloidal-dispersed state. This is explained by the fact that, in the course of interaction between the soil and sodium salts, the replacement of calcium cations by sodium takes place in the colloid complex, and this increases the charge of colloidal particles and their electrostatic repulsion. The soil mass becomes peptized, the peptization degree being determined by the ESP. The link between these three indices is very complicated. The dependence of peptizeable clay (as a percentage of the total clay content) on ESP and EC_e of chloride solutions is shown in Figure2. Maximum clay peptization is confined to high values of ESP (>60%) and low values of EC_e (<0.5 dS/m).

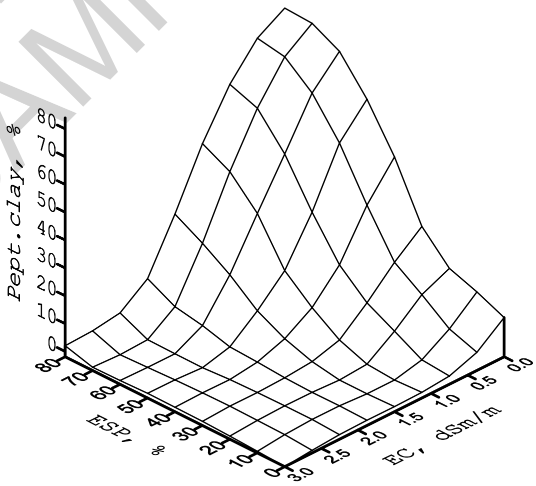

Figure 2. Peptizeable clay in chlorid solutions

The natric/solonetzic horizon in wet conditions is plastic, sticky, viscous, and shows high swelling. The latter leads to low porosity and aeration, and to reduced air exchange, causing oxygen deficiency in plants. In dry conditions the soil mass of this horizon shrinks to a great extent; the surface is cracked and the soil structure breaks up into blocks, especially on cropland. Shrinking leads to deformation and in many cases breaks the plant roots. The hardness of the horizon is increased and the soil becomes more resistant to treatment.

Hydrological factors: Alkali soils are 10–15% less permeable to water than non-alkali soils. The higher the ESP, the lower the water permeability. Infiltration rates in the solonetzic horizon of soils with ESP of up to 10% range from 0.430 to 0.108 mm min^{-1} after six hours, but where ESP reaches 20% infiltration stops completely. Low permeability causes most of the rainfall to flow over the soil surface rather than into the soil, so that the total water supply in alkali soils is always lower than in surrounding zonal soils. Another adverse feature of these soils is a high content of unavailable moisture, accounting for 12–17% (whereas in chernozems this is 8–12%). The suction force of crop roots is insufficient to take up the moisture. The amount of active water in alkali soils is always lower than in other soils. For this reason, the phenomenon known as "physiological drought" may be observed in alkali soils.

Physiological factors: The majority of alkali soils contain water-soluble salts, concentrations of which can be toxic for plants. Only salt-tolerant plants are suitable for growing on these soils. The leaching of excess toxic salts from the root zone is urgently required to improve the soils for cultivation. The soil solution in the solonetzic and overlying horizons is always alkaline and contains sodium carbonate; the pH value reaches 9–10. This has an adverse effect upon the growth and development of the root systems. Cation nutrition imbalance occurs, especially when ESP exceeds 40% and EMgP is greater than 80%. There has been little research into any linear dependence between ESP and crop growth and development, but it is known, that crops such as Melilotus albus, Agropyron spp., Elymnus elongatum, and Elymus angustus are suitable for growing on soils with ESP above 60%. Wheat, cotton, lucerne, barley, and tomatoes can grow on soils where the content of exchangeable sodium does not exceed 60%. Rice, oats, and clover are usually grown on soils with ESP up to 40%. There is also evidence that ESP affects the properties that limit the productivity of soils.

Complicated soil cover pattern factor: As a rule, alkali soils are distributed in a very complex pattern in a given area, and their share of the soil cover may range from a very small proportion to 90% or more. Alkali soils occur among the other soils as spots in different configurations (frequently circular or oval) and size (from one to several tens of square meters). Due to their specific water-physical properties the range of soil moisture adequate for cultivation is very small and the period when moisture is appropriate may be short. The period of "maturity for cultivation" comes later in the case of solonetz soils than for the surrounding zonal ones. When the period of "maturity" appears, the surrounding soils may dry out; tillage of soils in the solonetz complex may be impracticable where the soils are impassible for agricultural machines. Moreover, precipitation may form a crust on the surface of these soils that hinders the germination of seeds. It is evident that the growth and development of crops on alkali and zonal soils take place at different times, and this reduces yields.

3. Amelioration of Alkali Soils

3.1. Theoretical Aspects of Amelioration

To eliminate the effect of limiting factors it is necessary to prevent the causes of unfavorable water-physical properties and, in the first instance, to avoid peptization of dispersed systems. This can be done either by adding calcium-containing amendments, or by activating the soil's calcium content to incorporate calcium into the soil adsorption complex (SAC) of the solonetzic horizon. The calcium will replace the exchangeable sodium in the soil, thus reducing the charge of colloidal particles, which provides for their coagulation. In turn, this leads to an improvement of the soil structure, decreases the exchangeable mass and hardness, and enhances water permeability and air exchange. It leads to the extension of the range of active water. The improvement of infiltration properties helps leach toxic salts out of the plow layer. In addition, the presence of calcium salts has a favorable effect upon the cation nutrition balance of plants, and helps neutralize sodium carbonate.

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Biographical Sketches

Irina Nikolaevna Lyubimova was born in 1943. In 1965 she graduated from the Department of Biology and Soil Science, Moscow State University and started work as a researcher at the Dokuchaev Soil Science Institute. At present, she is the Head of the Laboratory of the Genesis and Amelioration of Solonetzic Soils. She is a Candidate of Biology, and author of about 100 works devoted the genesis and agrogenic transformation of the soils of solonetzic complexes.

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 that time, 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.

Leonid Fedorovich 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.