Magnesium in Salt-Affected Soils

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Diverse opinions on the effects of magnesium on soil fertility are reported in the literature (ANTIPOV-KARATAEV & FILIPOVA, 1955; ARANY, 1931; DARAB, 1980; DARAB & REMÉNYI, 1974; GEDROITZ, 1955; KELLEY, 1951; KREYBIG, 1935; MONDAL, 1972; POLYNOV, 1956; SZABOLCS, 1961, 1979, 1989).

The diversity of opinions on the effects of magnesium may be traced back to the fact that magnesium soils with different genesis and properties were brought together into one group, regardless of the soil forming processes, the sources and the means of magnesium enrichment, and the type and mobility of magnesium compounds accumulated.

The term *magnesium soils* includes:

1. Solonchak soils where magnesium accumulates in the form of inorganic salts (mainly magnesium sulphate and magnesium chloride). The high concentration of magnesium salt in the soil solution of magnesium solonchak is toxic to plant growth, thereby having a direct physiological effect (KOVDA et al., 1967).

2. Hydromorphic soils - with dark colour and heavy texture - which contain increased quantities of total and exchangeable magnesium. The fertility of these soils is influenced by the poor water conductivity and by the limited mobility of soil moisture (EMERSON & SMITH, 1970; DARAB & REMÉNYI, 1978). Some authors relate the poor water physical properties with the increase in the degree of magnesium saturation (JOFFE, 1949; OVCHARENKO et al., 1974). Other publications refer to the formation of magnesium - soil - organic matter complexes with high stabilities. These magnesium complexes, together with the layer silicates of the clay fraction, form compounds of great hydrability (EMERSON & SMITH, 1970). There is evidence in the literature indicating a relationship between the increase in the amount of swelling layer silicates and the inhibited water movement in these soils.

3. There are soils which have a high degree of magnesium saturation as well as a large variation of sodium saturation. These soils have every morphological feature of the solonetz profile. Some authors suggest similarities between the

behaviour of magnesium and sodium ions in the solonetz formation (MÁTÉ, 1955). Others regard the increase in the degree of magnesium saturation as the first stage in the solonetz forming processes (ARANY, 1931). POLYNOV (1956) assumes that exchangeable magnesium accumulates during the leaching of salt-affected soils. ANTIPOV-KARATAEV & FILIPOVA (1955) and ANTIPOV-KARATAEV & MAMAEVA (1958) proved that the morphology of solonetz soils - having a high degree of magnesium and low degree of sodium saturation - is the relic of a former stage of solonetz soil formation connected with the enrichment of exchangeable sodium.

The only common feature in all of these soils is that they contain increased amounts of magnesium compounds and the increased amounts of mobile magnesium compounds may influence their fertility.

The formation and accumulation of magnesium compounds are due to a large number of geochemical and soil forming processes taking part in the upper strata of the earth's crust.

Discussing the influence of magnesium compounds on soil properties, studies have to be carried out on:

I. The types and sources of magnesium compounds;

II. The stability of magnesium-bearing constituents and the mobility of the weathering products;

III. The effect of mobile magnesium compounds on the properties of soils and plant growth.

The Types and Sources of Magnesium Compounds in Soils and Soil Forming Rocks

Magnesium is the fifth frequent constituent of compounds among the elements in the earth crust (Table 1). The relatively high abundance of magnesium in the crust and mantle of the earth leads to its occurrence in numerous silicate minerals.

Because of the high electronegativity of this cation, most magnesium minerals contain Mg^{2+} ions in octahedral coordination with the oxygen atom.

Table 1

Average chemical composition of the earth's crust

Element	Percentage	Element	Percentage	Element	Percentage
SiO_2	59.07	CaO	5.10	TiO_2	1.03
Al_2O_3	15.22	MgO	3.45	P_2O_5	0.30
Fe_2O_3	3.10	Na_2O	3.71	MnO	0.11
FeO	3.71	K_2O	3.11	H_2O	1.30

During the geological periods the magma forming processes, the volcanic and post volcanic phenomena may facilitate the formation of magnesium-containing minerals with different stability. When the cooling of magma is rapid the ratios of magnesium and iron to silicium are high in the melts olivines form as the first stage of crystallization of basic volcanic rocks (Table 2). These minerals are rich in magnesium and have low stability in their crystallic lattice.

Table 2

Average elemental composition of some igneous rocks

(TUREKIAN & WEDEPOHL, 1961, cit.: GREENLAND, D. J. & HAYES, M. H. B., 1978)

Element	Ultrabasic rocks	Basaltic rocks	High Ca granatic rocks	Low Ca granatic rocks
Si	205	230	314	347
Al	20	78	82	72
Fe	94	86	30	14
Ca	25	76	25	5
Mg	204	46	9	2
Na	4	20	28	26
K	0.04	8	25	42
Ti	0.30	14	3.40	1.20
Mn	1.60	1.50	0.54	0.40
P	0.22	1.10	0.92	0.60

**concentration in ppm*

Table 3

Average chemical composition of igneous and sedimentary rocks, %

Element	Igneous rocks			Sedimentary rocks		
	Granite	Grandiorite	Basalt	Sandstone	Clay stone	Limestone
SiO_2	70.77	65.69	51.55	79.63	61.16	5.24
TiO_2	0.39	0.57	1.48	0.15	0.68	0.06
Al_2O_3	14.59	16.11	14.95	4.85	16.21	0.82
Fe_2O_3	1.58	1.76	2.55	1.09	4.23	0.55
FeO	1.79	2.68	9.10	0.31	2.58	0.55
Fe	2.50	3.31	8.86	0.99	4.96	0.43
MnO	0.12	0.07	0.20	Traces	Traces	Traces
MgO	0.89	1.93	6.63	1.18	2.57	7.96
CaO	2.01	4.47	10.00	5.59	3.27	42.97
Na_2O	3.52	3.74	2.35	0.46	1.37	0.05
K_2O	4.15	2.78	0.89	1.33	3.41	0.33
P_2O_5	0.19	0.20	0.30	0.08	0.18	0.04
CO_2				5.11	2.77	41.93

During the subsequent crystallization at lower temperature phases the proportion of magnesium to silicium decreases to the favour of iron. The hydrothermal alteration and weathering of minerals in igneous rocks leads to the formation of ferromagnesian minerals, magnesium layer silicates and carbonate minerals (Table 3). Silicium and calcium uptake promotes the transformation of olivines into pyroxenes. Amphiboles form in the presence of water. The water and potassium uptake of pyroxenes leads to the formation of biotites. The stability of ferromagnesian minerals increases with the increasing contribution of silicium and water in the minerals of basaltic rocks.

Chlorites and magnesium-rich members of smectites occur often in sediments and soils. The chemical weathering of the crustal minerals results in the removal of magnesium in solution, from which a large variety of minerals are accumulated in evaporite deposits. Among the magnesium minerals the following are the most abundant in weathered sediments and soils:

a) *Silicates.*

Magnesium is an important constituent of a large number of common rock-forming silicates. These include:

- the orthosilicates with olivine and garnet structures;
- the chain silicates with pyroxene and amphibole structure;
- the layer silicates, as biotite, chlorites and smectites.

In well-leached soil sediments and soils the magnesium content is less than 1% and it occurs mainly in the form of mafic minerals, such as augite, hornblende biotite, smectite.

b) *Carbonates.*

Dolomite ($CaCO_3{\cdot}MgCO_3$) and dolomitized calcite occur in some sediments, limestones and soils.

Dolomite usually forms under high pressure and at high temperature, and it may also form in the absence of biogenetic processes if the salt concentration of the solution is very high and the reaction of the media is strongly alkaline.

Dolomite of pedogenetic origin has been reported in some cases but usually it is inherited in soil parent materials from the dolomitic limestone and mantle rocks derived. 2% and more of the soils' magnesium content is in carbonate form in the carbonate-containing soils of moderate, semiarid and arid zones of the world. An other form of magnesium carbonate in soils could be magnesite, although it occurs in soils very rarely. It has a relatively good solubility and its solution is strongly alkaline.

c) *Sulphates and chlorides.*

The relatively high concentration of magnesium in mineralized surface and groundwater on the Earth and in the seawaters (Table 4) leads to the accumulation of magnesium sulphate and magnesium chloride in cases where evaporation is prevailing over leaching (which is the case of soils in the semiarid and arid zones and in the evaporite deposits.

Table 4
The chemical composition of oceans and sea waters

Name	Salt conc.	Na^+	Mg^{2+}	Ca^{2+}	K^+	CO_3^{2-}	SO_4^{2-}	Cl^-	Br^-
	g/l	percentage of total ion concentration							
Oceans*	3.3-3.7	30.6	3.7	1.2	1.1	0.2	7.7	55.3	0.2
Aral Sea	1.07	22.1	5.4	4.5	0.1	0.1	31.3	35.6	-
White Sea	2.6-3.0	30.7	3.75	1.2	0.9	0.1	7.9	55.2	0.1
Caspian Sea	1.27	24.5	5.8	2.6	0.6	0.9	23.8	41.8	0.05
Gulf of Mexico	3.55	30.8	3.6	1.2	1.1	0.3	7.5	55.2	0.2
Baltic Sea	0.72	30.5	3.5	1.7	0.1	0.1	8.0	55.0	0.1
Mediterranean Sea	3.73	30.6	3.65	1.2	1.1	0.2	7.9	55.1	0.2
Black Sea	1.8-2.3	30.5	3.70	1.4	1.2	0.5	7.5	55.1	0.2

* *average*

The total salt concentration and the chemical composition of ocean- and seawaters vary with the environment, however, it is characteristic that the concentration of magnesium salts is always more higher than the concentration of any other salts, with the exception of sodium salt concentration.

The Stability of Magnesium-Bearing Constituents of Rock and the Mobility of Weathering Products Containing Magnesium

In the recent period the weathering of rocks has been the primary source of soluble salts entering natural waters, sediments and soils.

The geochemistry of salts in a given place is determined by the mobility of the compounds formed, and by the sequence of precipitation of the weathering products. The mobility of the rock-forming elements depends on the following factors:

a) the stability of the crystalline network;
b) the radius of ions formed during weathering;
c) the charge of the ions formed during the weathering process.

These factors can be characterized by the energy coefficient, which is the proportion of energy contributed by any ion (though at infinity) to the formation of heteropolar combination.

FERSMAN (1934) calculated the energy coefficients of individual ions on the basis of known lattice energies of inorganic salts. These values were called "experimental energy coefficients" and can be considered as the most reliable figures. The energy coefficients of FERSMAN are closely related to the sequence of ion extraction from minerals, to the rate of ion migration and to the ability of the ions to accumulate in sediments and soils (Table 5).

According to FERSMAN's categories, the mobility of ions increases with the decrease in the energy coefficients of the ions, and decreases with the increase in the ion radius and valence. In extreme cases the salts produced by the weathering of rocks may accumulate in the place of their formation. This is the case when the insufficiency of precipitation prevents them to remove to a distance. More frequently they are transported by natural waters and are redistributed. The distribution of the transported weathering products in a region is characterized by the sequence of the migration categories of elements, as follows:

Table 5

Sequence of ion-extraction during weathering

(according to FERSMAN, 1934)

Sequence	Ions	Energy coefficient	Sequence	Ions	Energy coefficient
I.	Cl^-, Br^-	0.23	II.	Na^+	0.45
	NO_3^-	0.18		K^+	0.36
	SO_4^{2-}	0.66		Ca^{2+}	1.75
	CO_3^{2-}	0.77		Mg^{2+}	2.10
III.	SiO_3^{2-}	2.75	IV.	Fe^{3+}	5.15
				Al^{3+}	4.25

1.	Virtually non-leachable	Si of quartz
2.	Slightly leachable	Fe, Al, Si
3.	Leachable	Si, P, Mn
4.	Highly leachable	Ca, Na, K, Mg, Cu, Co, Zn
5.	Very highly leachable	Cl, Br, J, S, C, B

The absolute and relative participation of elements in the formation of natural waters and saline soils are directly related to the categories which were determined empirically by Polynov and Kovda. The main compounds contributing to contemporary salt accumulation are the salts formed from the elements of migration categories 4. and 5.

The type of salt accumulation depends on:

a) the quantity of water soluble salts,

b) the chemistry of salinization;

c) the vertical and horizontal distribution of accumulated salts in sediments and soils.

Climatic, geological, geomorphological and hydrogeological conditions are factors determining the type and degree of salinization.

Magnesium occurs in a high proportion of the minerals in mafic igneous rocks.

Igneous rocks on the Earth's surface transform mainly due to the chemical weathering of primary minerals of magmatic origin. The form and rate of mineral decomposition depend on the environment and on the natural conditions the weathering takes place, but they are determined by the properties of the relative stability of minerals against destruction.

In the case of magnesium silicates and ferromagnesian minerals, the degree of basicity is the factor which determines the relative stability of the crystal network. The degree of the mineral's basicity can be expressed as the ratio of basic cations to the Si^{4+} ions. The stability of the silicate minerals increases with the decrease in their basicity. The decrease in the basicity and increase in the stability of the minerals in weathered mafic rocks are usually connected with the hydration and decomposition of primary minerals and with the formation of sedimentary rocks. The part of sedimentary rocks in the Earth mantle is estimated to be 5-10%. They form under the influence of hydrospheric and atmospheric factors and the weathered primary rocks tend to accumulate on the surface of the Earth. Sedimentary rocks cover 70-80% of the land area of the Earth as a result of the processes determining the decomposition of primary minerals and the sedimentation of the weathering products. Sedimentary rocks differ from igneous rocks in their chemical and mineralogical compositions (Table 6). Sedimentary rocks contain more quartz than rocks of volcanic origin.

Primary minerals, as feldspars, pyroxenes, amphiboles, occur in small quantities in the sand and silt fractions. They contain layer silicates sometimes in a high ratio in the clay fraction of sediments.

Most soils have been formed from sediments. The chemistry and mineralogy of these soils are determined by the mineral composition of the parent rocks and by the soil-forming processes.

Table 6

Average mineralogical composition of igneous and sedimentary rocks, %*

	Igneous rocks	Shale	Sandstone
Feldspars	59.5	30.0	11.5
Amphiboles and pyroxenes	16.8	-	traces
Quartz	12.0	22.3	66.8
Micas	3.8	-	traces
Titanium minerals	1.5	-	traces
Apatite	0.6	-	traces
Clay	-	25.0	6.6
Limonite	-	5.6	1.8
Carbonates	-	5.7	11.1
Other minerals	5.8	11.4	2.2

The types and ratios of the inherited primary minerals are reflected in the composition of sand and silt fractions (Table 7).

Table 7

Mineralogical composition of soil particles in the coarse fractions, %

Soil type and horizon	**Particle size range**	**Quartz**	**Feld-spars**	**Mus-covite**	**Pyroxenes and amphi-boles**	**Other min-erals**
Meadow soil						
A-horizon	> 0.1	< 60	5-10	10-20	5-10	5-10
	0.1 - 0.05	< 60	5-10	10-20	5-10	5-10
	0.05-0.02	< 60	5-10	5-10	5-10	5-10
B-horizon	> 0.1	< 60	5-10	10-20	5-10	5-10
	0.1 - 0.05	< 60	5-10	10-20	5-10	5-10
	0.05-0.02	< 60	5-10	5-10	5-10	5-10
C-horizon	> 0.1	< 60	10-20	10-20	5-10	5-10
	0.1 - 0.05	< 60	10-20	10-20	5-10	5-10
	0.05-0.02	< 60	10-20	10-20	5-10	5-10
Solonetz soil						
B-horizon	> 0.1	< 60	10-20	10-20	5-10	5-10
	0.1 - 0.05	< 60	5-10	10-20	5-10	5-10
	0.05-0.02	< 60	5-10	5-10	5-10	5-10
C-horizon	> 0.1	< 60	10-20	10-20	5-10	5-10
	0.1 - 0.05	40-60	10-20	20-40	5-10	5-10
	0.05-0.02	< 60	5-10	10-20	5-10	5-10
Solonchak soil						
B-horizon	> 0.1	< 60	5-10	5-10	5-10	5-10
	0.1 - 0.05	< 60	5-10	10-20	5-10	5-10
	0.05-0.02	< 60	10-20	5-10	5-10	5-10

The coarse fractions are dominated by quartz, followed by muscovite and feldspars (10-20 and 5-10%, respectively). Pyroxenes, amphiboles and opaque minerals may also be found with 5-10%. Microscopic investigations of coarse fractions were carried out from soil samples with hydromorphic origin. The X-ray analyses data of samples with different ranges of particle sizes give similar results as the microscopic investigations (Table 8).

As it can be seen from Table 8, the coarse fractions of soil samples are dominated by quartz and they contain some micas, feldspars and chlorites. The quantity of quartz decreases with the decrease in particle sizes. Feldspars are found in practically the same amount in each fraction with different ranges of particle sizes. Clay minerals may occur in samples with 5-10 µ size range and they dominate in the fraction of clay sizes.

Table 8

Mineralogical composition of soil particles with different ranges of size in a hydromorphic (meadow) soil

Horizon	Range of sizes Ø mm	Mineralogical composition of soil particles of different ranges of size*
A-horizon	< 0.001	M > Mo > Cl = Q = Fsp
	0.001 - 0.005	Q > M = Fsp > Cl
	0.005 - 0.010	Q > M = Fsp > Cl = C
	0.010 - 0.050	Q > Fsp > M = Cl = C
	0.050 - 0.100	Q > Fsp > M = Cl = C
	0.100 - 0.200	Q > Fsp > M = Cl = C
	> 0.200	Q > Fsp > M = Cl = C
B-horizon	< 0.001	M > Mo > Cl = Q = Fsp
	0.001 - 0.005	Q > M = Fsp = Cl
	0.005 - 0.010	Q > Fsp > M = Cl
	0.010 - 0.050	Q > Fsp > M = Cl = C
	0.050 - 0.100	Q > Fsp > M = Cl = C
	0.100 - 0.200	Q > Fsp > M = Cl = C
	> 0.200	Q > Fsp > M = Cl = C
C-horizon	< 0.001	M > Mo > Q = Fsp > Cl
	0.001 - 0.005	Q > M > Fsp > Cl
	0.005 - 0.010	Q > M = Fsp > Cl
	0.010 - 0.050	Q > Fsp > M = Cl = C
	0.050 - 0.100	Q > Fsp > M = Cl = C
	0.100 - 0.200	Q > Fsp > M = Cl = C
	> 0.200	Q > Fsp > M = Cl = C

*Q: quartz; M: mica and hydromica; Mo: montmorillonite; Fsp: feldspars; Cl: chlorite; C: carbonate

Magnesium is a constituent of the crystal network of trioctahedral layer silicates formed by the substitution of divalent magnesium for trivalent cations in the octahedral sheet. Among the magnesium-rich trioctahedral minerals, biotite is one of the representative minerals of sediments and soils. In biotites 20-60% of the occupied sites contain magnesium.

Trioctahedral micas are common constituents of igneous and metamorphic rocks. They are readily weathered, so trioctahedral micas and hydromicas are found seldom in sediments and soils.

Other magnesium-rich layer silicates of sediments and soils are vermiculites, smectites and chlorites (Table 9).

Macroscopic vermiculite is a 2:1 trioctahedral layer silicate. Clay-sized vermiculites are frequently found in soils. They can be either dioctahedral or tri-

Table 9

Elemental composition of some clay minerals, in percentage (cit in: DEGENS, 1968)

Element	Allophane	Kaolinite	Halloysite	Montmorillonite	Vermiculite	Illite	Chlorite
SiO_2	33.96	45.44	44.08	51.14	35.92	49.26	26.68
Al_2O_3	31.12	38.52	39.20	19.76	10.68	28.97	25.20
Fe_2O_3	traces	0.80	0.10	0.83	10.94	2.27	-
FeO	-	-	-	-	0.82	0.57	8.7
MgO	-	0.08	0.05	3.22	22.00	1.32	26.96
CaO	2.26	0.08	-	1.62	0.44	0.67	0.28
Na_2O	-	0.66	0.2	0.04	-	0.13	-
K_2O	-	0.14		0.11	-	7.47	-
H_2O	33.12	14.20	16.18	22.80	19.84	9.25	11.7

octahedral, but the dioctahedral form is more frequent than the trioctahedral variety. Trioctahedral vermiculite of soils can be characterized by the formula

$$X_{1.1}\left(Al_{2.3}Si_{5.7}\right)\left(Al_{0.5}Fe^{3+}_{0.7}Mg_{4.8}\right)O_{20}(OH)_4nH_2O$$

The formula X represents the ratio of exchangeable cations. One part of magnesium can be found in clay vermiculite as an interlayer cation which is easily exchangeable by other cations from the intermicellar solution in soil-solution systems.

Smectites occur only as silt and clay-sized particles. They are 2:1 layer silicates with variable basal spacings and cation exchange properties. The basal spacing of smectites depends on the composition of interlayer cations and the amount of water associated with exchangeable ions. Magnesium ions occur in smectites in exchangeable form and in the octahedral sheets of the crystal network, replacing aluminium ions. A typical example of magnesium-rich smectites is montmorillonite. The dioctahedral layer composition, involving 0.4-0.6 units of octahedral magnesium, can often be found among soil montmorillonites.

According to the literature data, smectites with trioctahedral structure are found seldom in soils and sediments.

The abundance of exchangeable Ca^{2+} and Mg^{2+}, silica-rich media and hydromorphic environment promote the formation of expansive forms of montmorillonites.

Among the magnesium-rich minerals, chlorites occur extensively in soils, partly inherited from parent rocks, and partly formed during soil-forming processes. The MgO content of chlorites can be as high as 27%. Structural studies proved that most of the members in the chlorite group have a structure based on

2:1 units, similar to those in mica, but with the interlayer space increased and containing a brucite-like hydroxide interlayer. Different members of chlorite minerals can be distinguished by their structure and chemistry. The octahedral sheets may have a dioctahedral or trioctahedral structure. Trioctahedral chlorites occur more often in rocks than the dioctahedral form of the crystal network, whereas the situation is opposite in cases of soils.

The elemental composition of chlorite minerals varies in a wide range. A basic formula for trioctahedral chlorite may be: $(Al_2Si_6)\ Al_2Mg_{10}O_{20}\ (OH)_{16}$. Further distinction can be made if ferrous or other divalent cations replace Mg^{2+}, and ferric or other trivalent ions replace the Al^{3+} in the crystal network. Samples with much Al replacing Mg tend to take the replacement further and to be dioctahedral in either one or both of the sheets. The terminal member of this series is characterized by the formula:

$$Al_{4.4}\,(OH_{12}\,(Al_{1.2}Si_{6.8})\ \text{-}\ Al_4O_{20}\,(OH)_4$$

Most soil clay fractions contain mixtures of minerals including some transitional forms of layer silicates, for instance, swelling chlorite might be formed. The product of the supposed process has a 2:1 structure with interlayer brucite islands and hydrated exchangeable magnesium ions. The ratio of the octahedral magnesium hydroxide and the exchangeable magnesium ions depend on the pH value and on the magnesium ion concentration of the intermicellar solution. Alkaline reaction and high magnesium concentration favours the formation of chlorite; the decrease in pH value and magnesium concentration of the solution promotes the destruction of the brucite layer and the desorption of magnesium ions.

Among magnesium carbonate containing minerals, dolomite has a molar ratio of $CaCO_3{:}MgCO_3 = 1{:}1$ in an ideal case. This ratio is determined by the crystal structure of dolomite, and it varies between 0.91 and 1.38. The thermodynamic solubility product of dolomite depends on the composition and structure of the mineral and it varies from $3.6 \cdot 10^{-17}$ to $4.6 \cdot 10^{-20}$.

Dolomite with regular structure forms under high temperature (200-500 °C) and pressure. Dolomites having irregularities in their structure may develop due to the special properties of the solution. Because of its properties it is probable that the dolomite in soil is inherited from the parent rock. Dolomite does not decompose easily, due to low solubility. Dolomite rocks are moderately hard and are less resistant against disintegration.

In some cases the distribution of carbonate minerals among fractions of different sizes is taken as a measure of the distribution of carbonates of pedogenetic origin or inherited from the parent rock (Table 10). Due to the disintegration of dolomite rocks, the disintegrated particles of primary minerals may occur in the fine fraction of sediments and soils. A better result can be obtained

Table 10

The distribution of carbonate minerals in the sand and silt fractions of salt-affected soils (SZENDREI, 1977)

Horizon	Depth of sampling cm	Sand fraction			Silt fraction		
		Dolomite	Calcite	Total carbonate *	Dolomite	Calcite	Total carbonate *
Solonchak solonetz soil							
A	0-5	1.6	0.7	2.4	4.5	0.3	5.2
B_1	5-15	1.5	1.2	2.8	5.0	0.9	6.3
B_2	15-31	7.2	4.1	11.9	11.2	4.2	16.4
BC	31-44	9.1	5.5	15.4	20.1	6.4	29.3
C	44-55	7.9	5.7	14.3	18.5	6.0	26.1
Solonchak soil							
A	0-3	12.6	0.6	14.4	9.5	1.3	11.6
	3-11	6.7	2.4	10.3	12.3	2.8	16.2
B_1	11-17	7.6	3.2	11.4	-	-	-
	17-31	8.4	3.9	13.0	19.0	6.4	27.0
B_2	31-55	12.8	5.6	19.5	26.1	8.8	36.1
C	55-70	6.7	6.1	14.0	23.9	5.7	31.7

by comparing the dolomite contents in coarse fractions of parent material and in the different horizons of soils (Figure 1).

Magnesium carbonate has higher solubility than dolomite and calcium carbonate. The concentration product of magnesium and carbonate ions amounts to 2.10^{-4} at 20 °C. The concentration of water saturated with magnesium carbonate is about 1.2 g/l. During the dissolution, alkaline hydrolysis takes place and the saturated solution of magnesium carbonate may be highly alkaline. The accumulation of magnesium carbonate in a free form is very rare in soils. This is due to the adsorption of magnesium by clay and also the formation of dolomitized calcites and dolomite during the accumulation of carbonates. The solubility of calcites dolomitized to different degrees is a complex function of the chemistry and structure of the carbonates.

In some cases it has been shown that Mg^{2+} favoured the precipitation of aragonite over calcite. Calcium carbonate precipitated in $MgCl_2$ solution is more soluble than calcite. The effect of Mg^{2+} ion concentration on precipitation and dissolution is a combined phenomena. The dissolution of carbonate minerals depends on the specific surface, on the magnesium content of the minerals and on the chemistry of the solution in equilibrium with the solid phases.

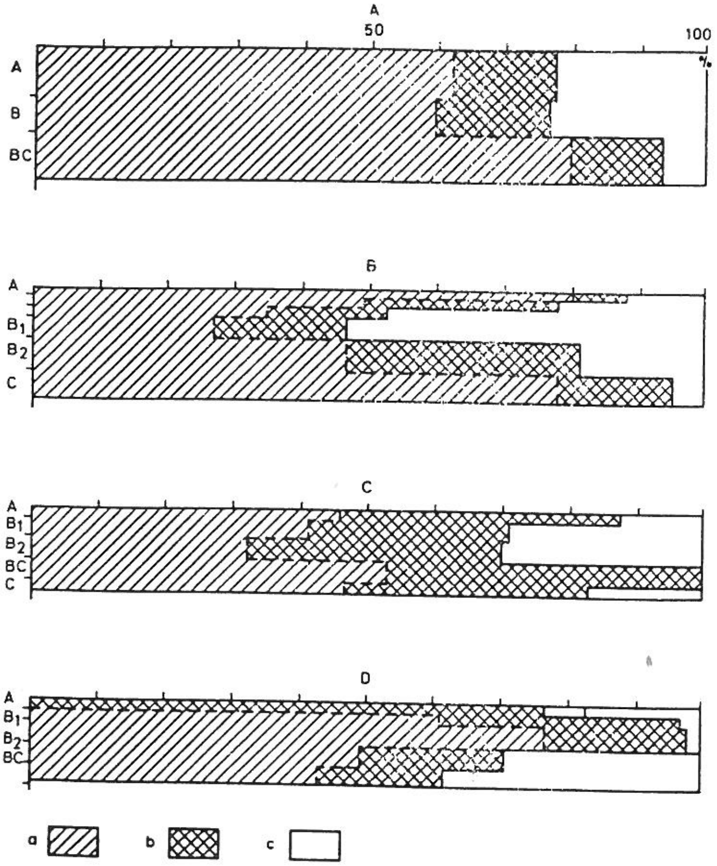

Figure 1

Primary carbonates as a) $CaCO_3$, b) dolomite content, and c) calcite content of pedogenetic origin in the samples of hydromorphic soils with a diameter of > 0.01 mm. A. Meadow alluvial soil. B. Solonchak soil. C. Solonchak solonetz soil. D. Solonetz soil with shallow A horizon

Inorganic salts of magnesium occur mainly in seawater, and in the groundwater, sediments, and soils of deserts and semi-desert regions. The mobility and role of magnesium salts in soil-forming processes depend on the kind of anion to which the magnesium ion is bound. Saturated solutions of magnesium carbonate, magnesium sulphate and magnesium chloride have concentrations of 1.2 g/l, 262 g/l and 354 g/l, respectively. Magnesium carbonate hydrolyses in water with an alkali reaction. Magnesium sulphate and magnesium chloride solutions have neutral or slightly acidic reactions. During the decomposition of primary minerals the magnesium readily goes into solution. Due to the good solubility of inorganic magnesium salts, the weathering products of magnesium-containing minerals have high mobility and they accumulate in seawater, in waters, in soils and sediments if the climate and the geomorphological conditions favour the accumulation of salts. Magnesium sulphate and magnesium chloride usually precipitate together with other readily soluble salts, either as separated minerals or as complex crystals. In the evaporites of seawater we may find, for example, besides the different forms of magnesium sulphate, magnesium chloride and alkalihaloides, the crystals of complex minerals, such as kainite, carmallite, boracite, etc.

The Effect of Mobile Magnesium Compounds on the Properties of Soils and Plant Growth

The sources of magnesium compounds in soils are primary minerals or their weathering products in soil-forming rocks. The magnesium in these compounds may have different mobilities. The mineralogical association of parent material and soil, the intensity of the physical and chemical weathering have an effect on the particle size distribution as well as on the movement and balance of chemical elements in soils.

The mobility of magnesium and of other elements is determined by the chemical bonds within the minerals.

The magnesium reserves of soils can be distributed in three groups, according to their mobility:

a) Mobile magnesium compounds, which include the readily soluble inorganic magnesium salts and the exchangeable magnesium in soils.

b) Short-term reserves of mobile magnesium. The magnesium in the layer silicates of clay fractions, and the magnesium in the fine-grained, dolomitized calcite belong to this group.

c) The potential reserves of mobile magnesium. The magnesium of minerals in the non-clay fractions of the soil belongs to this kind of magnesium compound.

The quantities and ratios of soil magnesium with different mobility vary in a wide range (Table 11). In a meadow solonetz soil formed under the influence of mineralized groundwater the total magnesium has a minimum value in the B horizon and the highest values were measured in the C horizon. The magnesium concentration in clay fractions is less than in the non-clay fractions. The ratio of these two values decreases from the B_2 to C horizon. The B_1 horizon of this soil is an exception, where the bulk of soil magnesium occurs in the clay fraction and in the form of mobile magnesium. The same rule can be supposed from the mineralogical composition of the clay fractions of the different soil horizons (Table 12).

The enrichment of magnesium in clay is not limited to the accumulation horizon of the solonetz soils. In the B horizon of a meadow soil, mobile mag-

Table 11

Magnesium content in a solonetz soil (Profile No. B-29) and in its clay fraction

Depth of sampling, cm	Particles Ø < 1μ, %	Total Mg in soil, meq/100g	Mg in clay		Exchangeable Mg	Soluble Mg
			meq/100 g clay	meq/100 g soil	meq/100g soil	
8-16	53.52	79.37	69.44	31.17	17.12	0.30
26-37	60.44	81.85	71.93	43.47	30.30	0.24
48-55	53.72	40.18	65.48	35.17		0.31
75-85	39.22	85.32	79.37	31.13		2.84
94-105	40.62	76.89	77.38	31.43		2.52
117-126	39.17	147.33	71.93	28.17		0.25
135-145	42.29	102.70	81.35	34.40		

Table 12

Mineralogical composition of the clay fraction of a solonetz soil (Profile No. B-29), in percentage

Depth, cm	Ill	Mo	Ill-Mo	Chl	Ill-Chl	Ill-Chl-Mo	Q	Fsp
8-16	70	-	5	5	5	-	10	5
26-37	45	20	10	10	5	-	5	5
48-55	45	20	10	10	5	-	5	5
75-85	40	30	5	10	5	-	5	5
97-105	40	30	5	10	5	-	5	5
117-126	40	30	5	10	5	-	5	5

Ill: illite; Mo: montmorillonite; Chl: chlorite; Q: quartz; Fsp: feldspars

nesium made up 30.6% of the total magnesium and the magnesium of the clay fraction amounted to 52.7% of the total magnesium content of the soil (Table 13).

Clay formation in the presence of magnesium may increase the ratio between the short-term reserves and potential reserves of mobile magnesium. Heavy-textured magnesium soils can differ in their morphological features as well as in their fertility. One group of these heavy-textured magnesium soils has every morphological feature of the solonetz soil and is classified as solonetz soil. The other group of these soils is formed under hydromorphic conditions. They are dark and heavy-textured, but do not possess the morphology of solonetz soils. They can be grouped with the so-called meadow soils and may be regarded as a kind of vertisol. Meadow soils and meadow solonetz occur

Table 13

Mineral composition and total magnesium in the samples with different size ranges of the B horizon of a meadow soil

Size range Ø μ	Particles, %	Total Mg meq/100 g sample	Total Mg meq/100 g soil	Mobile Mg meq/100g soil	Minerals*
< 1	44.1	118.6	52.3	30.37	Mo>M>Chl=Fsp=Q
1-5	12.3	61.6	7.5		Q>M=Fsp>Chl
5-10	9.4	31.7	3.0		Q>Fsp>M=Chl
10-50	14.3	38.7	5.5		Q>Fsp>M=Chl=C
50-100	1.5	34.2	0.53		Q>Fsp>M=Chl=C
100-200	0.1	36.2	0.04		Q>Fsp>M=Chl=C
soil			99.2		

*Mo: montmorillonite; M: mica and hydromica; Chl: chlorite; Fsp: feldspars; Q: quartz; C: carbonates

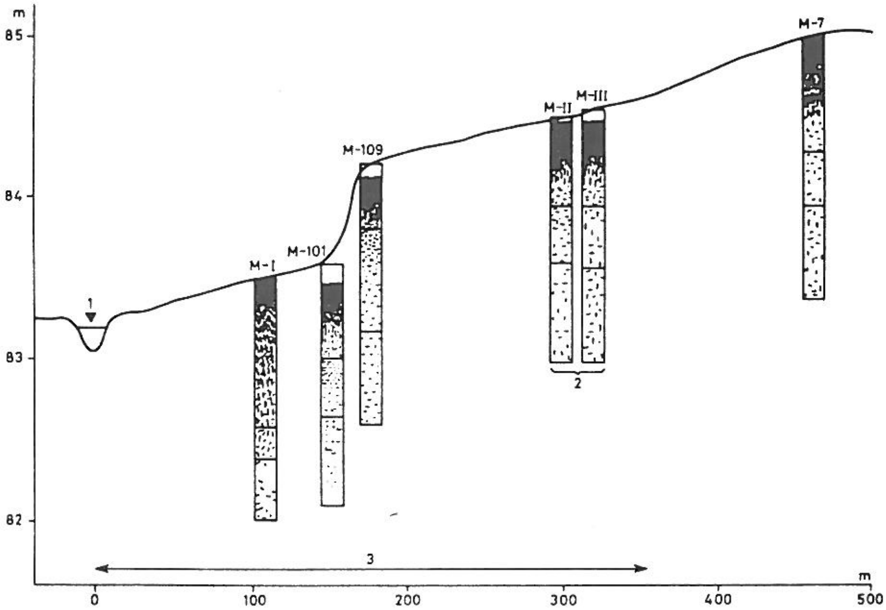

Figure 2

Soil profiles in vertical section M. Horizontal axis: distance from the river bed. Vertical axis: height above sea level. M-I. Meadow soil. M-101, M-109, M-II, M-III and M-7. Complex populations of middle and shallow solonetz soils. 3. Drainage effect of the river very often in the same area in complex population where the distribution of these two types of soils depends on the geomorphological, hydrological and topographical conditions of the places.

A typical example of the distribution of these soils is given in Figure 2. The soil profiles are meadow soil (M-I), middle and shallow solonetz soils. They form a cross-section, being in a 100 to 500 m distance from the riverbed. The difference between the elevation is about 3 m. The depth of the groundwater table varies between 2.5 and 3.5 m from the surface. All of the soil profiles have a heavy texture (Figure 3).

Water regulation and draining in the area were carried out in the second half of the last century. At this time a slow leaching can be considered to be the

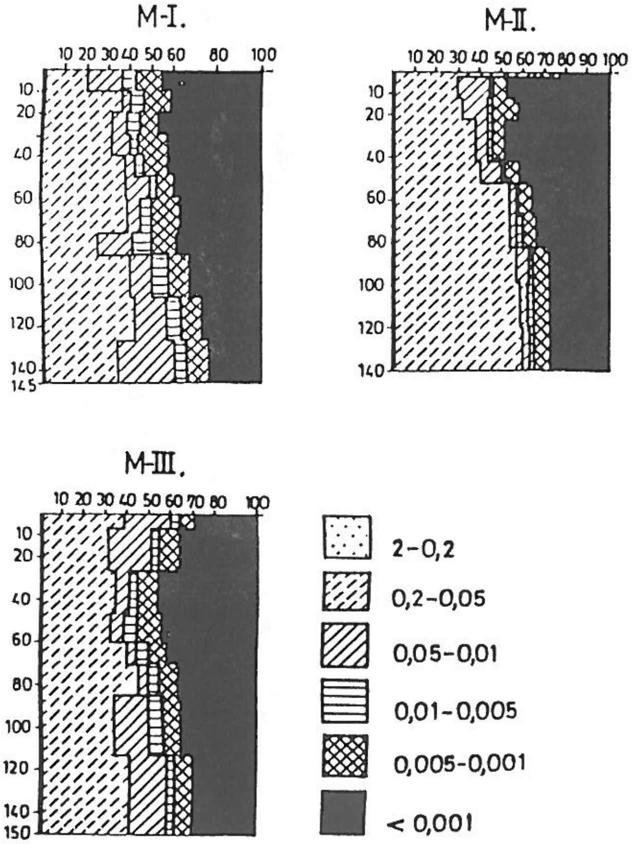

Figure 3
The mechanical composition of the soil profiles of the cross-section. Vertical axis: depth, cm. Horizontal axis: percentage

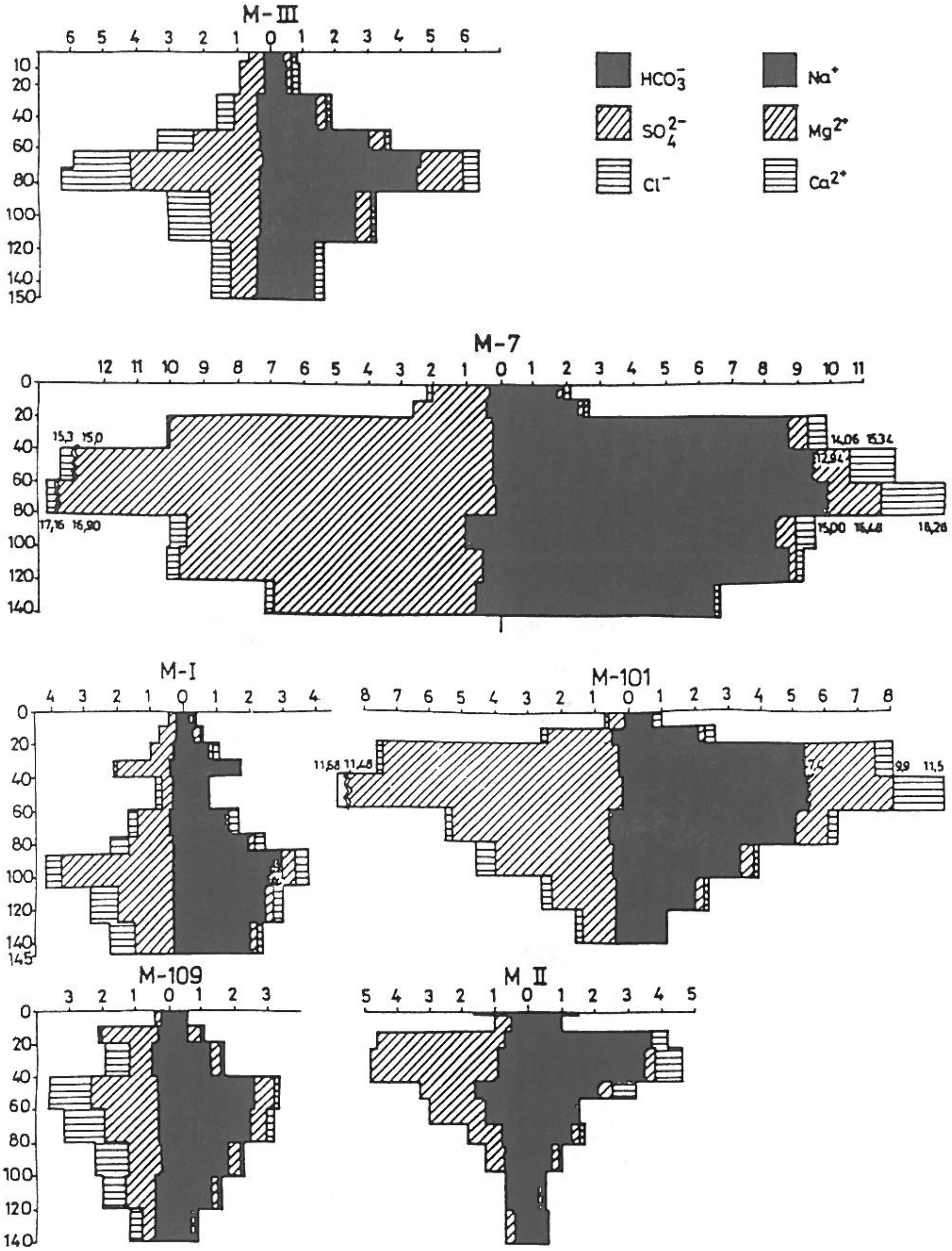

Figure 4

The chemical composition of soluble salts in meadow soil (M-I), Middle solonetz (M-101, M-109, M-III) and shallow solonetz (M-II, M-7) soil profiles. Horizontal axis: meq/100 g soil. Vertical axis: depth, cm.

dominating process. In the lower part of the cross-section, close to the riverbed, meadow soils occur. The middle and shallow soils can be found on the higher points of the cross-section and they form a complex population. The distribution of these two variations is determined by the micro-elevation of the places. The content of salts and the chemistry of soluble salts varied widely. The total quantity of soluble salts in the meadow soils is less than 0.1% in the surface horizon and it increases gradually along the soil profile having a maximum value in the C horizon (Figure 4).

The soluble salt content and the chemistry of the salts in solonetz soils vary depending mainly on drainage conditions and the degree of leaching. In the soil profiles of the cross-section, the quantities of soluble salts and the ratio of sodium salts increases with the decrease in the degree of leaching. With changes in the concentration and composition of soluble salts in the soils, the ratios of exchangeable cations change as well.

In the solonetz soil with poor drainage (M-7) the weighted average of mobile (exchangeable and soluble) sodium is the highest among the profiles of the cross-section and it has the lowest quantity of mobile magnesium (Table 14).

In solonetz soils with poor drainage (Profiles M-II and M-7) the morphology and the chemical properties of the soil are in harmony. In their accumulation horizon, which have a developed columnar structure, these soils contain a high amount of exchangeable sodium. In the well-leached solonetz soils (Profiles M-109, M-III) the weighted averages of mobile sodium are low, and the soils contain high quantities of mobile magnesium compounds. In these soils, besides the solodized A horizon and columnar structured B horizon, the sodium saturation degrees are very low (Figure 5).

The exchangeable magnesium percentage (EMgP value) is more than 30% in the B_1 horizon, and it surpasses 50% in the B_2, BC and C horizons.

Table 14

Some characteristics of soil profiles of the vertical section M

Profile No.	Soil type	Maximum total salt concentration, meq/l	Depth of salt accumulation, cm	Weighted average of mobile Na^+ meq/100g	Weighted average of mobile Mg^{2+} meq/100g
M-I	Meadow soil	50	80-120	5.12	8.05
M-101	Middle solonetz	150	20-60	6.20	15.25
M-109	Middle solonetz	40	40-80	3.79	17.94
M-II	Shallow solonetz	65	10-25	6.51	14.07
M-III	Middle solonetz	90	60-85	6.76	15.11
M-7	Shallow solonetz	20	20-80	20.94	6.73

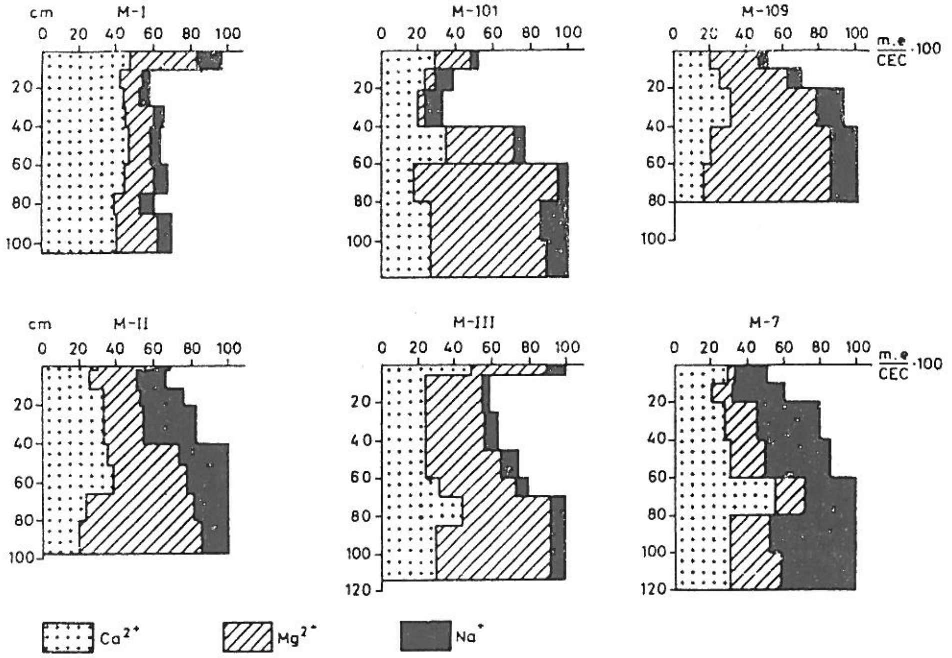

Figure 5
Exchangeable cations in the soil profiles of a cross-section

The solonetz morphology of the soils, having a low degree of sodium saturation, may be regarded as a relic of the earlier stage in the soil formation process, connected with the enrichment in exchangeable sodium.

In the meadow soil with no accumulation horizon, montmorillonite and the interstratified forms of illite-montmorillonite occur in larger quantities in the deeper layers than they are in the surface horizon.

The solonetz soils dominated by the leaching processes have a high amount of montmorillonite in their clay fraction. They contain, however, only a small quantity of the chlorite and the interstratified forms of illite-chlorite and illite-chlorite-montmorillonite. Where the sodium saturation is high in the solonetz soil, the quantities of the interstratified forms of the layer silicates are relatively high (Profile M-II).

It seems that a dynamic equilibrium exists between the soil solution, the surface of the clay particles and the crystalline lattice of the layer silicates in the soils. This interaction leads to the enrichment of soil minerals with magnesium during the accumulation period of the formation of salt-affected soils. During the leaching process, the magnesium from the octahedron of chlorite and the

Table 15

Quantities of minerals in the clay fraction of the investigated soils (g/100 g clay)

Profile No.	Depth, cm	Ill	Mo	Ill-Mo	Chl	Ill-Chl	Ill-Mo-Chl	Q	Fsp
M-I	0-10	40	10	10	5	5	-	20	10
	10-20	30	35	10	5	5	< 5	5	5
	20-30	25	40	10	10	5	-	5	5
	30-40	15	40	15	10	5	< 5	5	5
	40-60	15	30	15	15	10	< 5	5	5
	60-76	20	30	15	10	10	< 5	5	5
	76-85	20	25	15	15	15	-	5	5
	85-106	20	25	15	15	15	-	5	5
	106-127	20	25	15	15	15	-	5	5
M-II	0-2	35	15	20	10	10	-	5	5
	2-12	20	15	20	10	15	< 5	10	5
	12-22	20	20	20	10	15	-	10	5
	22-42	20	20	20	15	10	-	5	5
	42-52	20	25	20	15	10	-	5	5
	60-81	20	20	20	15	10	< 5	5	5
	81-98	20	20	20	15	10	< 5	5	5
M-III	0-7	25	35	10	5	10	-	10	5
	7-27	25	35	10	5	-	< 5	5	5
	27-47	30	45	15	5	-	-	5	-
	47-60	15	50	15	5	-	< 5	5	5
	60-70	15	50	15	5	-	< 5	5	5
	70-85	10	60	15	5	-	-	5	5
	85-115	5	65	5	10	-	-	10	5
	115-150	5	65	5	10	-	-	10	5

Ill: illite; Mo: montmorillonite; Chl: chlorite; Q: quartz; Fsp: feldspars

trioctahedral position of montmorillonite goes into exchangeable form to replace the leached exchangeable sodium and magnesium. The formed dioctahedral montmorillonite, with its high ability to swell, leads to the morphological features and poor water-physical properties of solonetz soil in spite of the decrease in sodium saturation degree.

In magnesium soils the quantities and ratio of soil magnesium with different mobilities vary in a wide range. The distribution of magnesium with different mobilities depends on:

a) the mineralogical composition of the parent rock;
b) the texture of soil;
c) the types and quantities of layer silicates in the clay fraction;

d) the dominating soil forming processes, such as accumulation and leaching of salts;

e) the hydromorphic influence of groundwater.

Magnesium salts usually accumulate in saline soils together with other readily soluble salts, such as sodium sulphate and sodium chloride.

The chemistry of soil salinization reflects the chemical composition of the salts and of the sources of soluble salts. The chemistry of the groundwater and the chemistry of the salt crust at the top of a meadow solonchak are very close to each other, as it is shown by the chemistry of 1:5 aqueous extracts of a solonchak soil from Kyzyl-Kum desert (Table 16). The ratio of equivalent concentrations of sodium to magnesium is practically the same in the groundwater and in the soil aqueous extract, but the soil is more chloridic and less sulphatic than the groundwater.

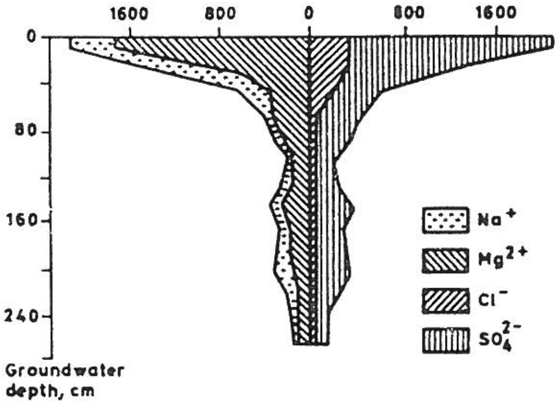

Figure 6
Salt content in the soil solutions of a crust solonchak
(Kara-Kalpak Experimental Station)

It seldom happens that the chemistry of soil salinization is characterized by the prevalence of magnesium salts. One example of this is given in Figure 6, which illustrates the chemistry of the soil solution in a crusty solonchak.

Magnesium sulphate and magnesium chloride are very toxic to plants. The toxic effects of magnesium chloride and magnesium sulphate can partly be traced back to their ready solubility, and partly to changes in the ion uptake of plants under saline conditions (Table 17).

The ion uptake of cotton plant increases with increasing soil salinity, and the ratio of ions in the dry matter shift in the favour of chloride, magnesium and sodium ions.

Table 16

Chemical composition of 1:5 aqueous extract of a solonchak*

(BOROVSKY & POGREBINSKY, 1958)

Profile No.	Depth of sampling, cm	Soluble salts	CO_3^{2+}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	$Ca^{2+}+Mg^{2+}$
7255	0-0.5	20.297	0.056	0.093	8.135	3.650	0.427	0.842	4.977
	0.5-5	10.740	traces	0.025	4.186	2.040	0.485	0.535	2.123
	5-10	11.379	-	0.034	4.030	2.210	0.482	0.560	2.064
	20-25	6.200	-	0.022	2.535	1.140	0.207	0.267	1.451
	35-40	4.730	-	0.023	1.850	0.902	0.148	0.230	1.032
	50-55	4.497	-	0.028	1.650	1.100	0.175	0.190	1.044
	85-90	2.475	-	0.028	0.955	0.625	0.052	0.112	0.656
	100-105	2.525	-	0.025	0.820	0.645	0.085	0.100	0.562
	125-130	2.292	-	0.028	0.821	0.560	0.040	0.091	0.592
Ground-water	545	31.14	-	0.85	8.23	11.43	0.61	1.52	7.54

* % in the 1:5 aqueous extract and g/l in the groundwater

Table 17

Mineral composition (as percent of absolute dry weight) of cotton plant at different phases of vegetation

(after KOVDA, 1947)

Condition of plant	**Vegetation phase**	**Mineral substances**	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	$\frac{Cl^-}{SO_4^{2-}}$	$\frac{Na^+}{Ca^{2+}+Mg^{2+}}$	$\frac{Na^+}{Mg^{2+}}$	$\frac{Mg^{2+}}{Ca^{2+}}$
Normal	sprouting	16.10	1.54	3.83	3.35	0.81	0.41	0.54	0.076	0.27	0.40
	budding	11.50	0.78	2.83	3.01	0.68	0.13	0.37	0.028	0.10	0.40
	ripening	10.60	0.40	3.23	3.95	0.35	0.04	0.17	0.008	0.06	0.15
Depressed	sprouting	17.00	1.56	2.03	1.83	0.87	0.54	1.04	0.144	0.33	0.78
	budding	16.40	1.97	3.47	3.89	0.94	0.40	0.77	0.064	0.23	0.40
	ripening	8.20	0.81	1.72	2.28	0.57	0.19	0.64	0.052	0.18	0.41
Strongly depressed	sprouting	20.73	2.84	3.05	1.26	1.10	1.22	1.30	0.32	0.51	1.65
	budding	17.14	2.04	5.94	2.10	1.47	0.63	0.50	0.12	0.23	1.15
	ripening	11.78	0.81	3.06	1.97	1.15	0.43	0.36	0.09	0.19	0.96

References

ANTIPOV-KARATAEV, I. N. & FILIPOVA, V. N., 1955. The effect of long-term irrigation on soils. (In Russian) Acad. Sci. USSR. Moscow

ANTIPOV-KARARTAEV, I. N. & MAMAEVA, L. Y., 1958. The role of magnesium in the formation of solonetz properties of soils. (In Hung.) Agrokémia és Talajtan. **7.** 1-14.

ARANY, S., 1931. Data to the behaviour of magnesium in soils. (In Hung.) Mezőgazdasági Kutatások. **4.** 439-450.

BOROVSKY, V. M. & POGREBINSKY, M. A., 1958. Drevnaa delta Syr-Dari i severnie Kyzyl-Kum. Izd. A.N.K.S.S.R. Alma-Ata.

DARAB, K., 1980. Magnesium in solonetz soils. In: Proc. Int. Symp. on Salt-Affected Soils. Karnal. India. 92-101.

DARAB, K. & REMÉNYI, M., 1974. Mineralogical composition of <1 μ fraction of magnesium soils in the Hungarian Lowland (In Russian). Trans. 10th Int. Cong. Soil Science. Moscow. **7.** 125-131.

DARAB, K. & REMÉNYI, M., 1978. The role of clay mineral composition in the formation and properties of some magnesium soils (In Hung.). Agrokémia és Talajtan. **27.** 357-378.

DEGENS, E. T., 1968. Geochemie der Sedimente. Stuttgart.

EMERSON, W. W. & SMITH, B. H., 1970. Magnesium, organic matter and soil structure. Nature. **228.** 453-454.

FERSMAN, A. E., 1934. Geochemistry. Leningrad.

GEDROITZ, K. K., 1955. On the adsorptive power of the soil. (In Russian) Selected works. Moscow. 243-283.

GREENLAND, D. J. & HAYES, M. H., 1978. The Chemistry of Soil Constituents. Wiley Interscience Publication. London.

JOFFE, J. S., 1949. Pedology. Pedology Publ. New Brunswick.

KELLEY, W. P., 1951. Alkali Soils. Reinhold Publ. New York.

KOVDA, V. A., 1947. Origin and Regime of Salt-Affected Soils. Vols. 1 and 2. (In Russian) Izd. Ak. Nauk SSR. Moscow.

KOVDA, V. A., VAN DEN BERG, C. & HAGEN, R. M. (eds.), 1967. International Source-Book on Irrigation and Drainage of Arid Lands in Relation to Salinity & Alkalinity. FAO/UNESCO.

KREYBIG, L., 1935. Vorkommen, Eigenschaften und wirtschaftlicher Wert von Magnesia und Kaliboden in Ungarn. Trans. 3rd Int. Cong. Soil Sci. **1.** 353-357.

MÁTÉ, F., 1955. Magnesium ion accumulation in the adsorption complex of meadow soil of the Tisza Valley (In Hung.). Agrokémia és Talajtan. **4.** 291-298.

MONDAL, R. C., 1972. Effect of high Mg waters on a bentonite clay complex as influenced by $CaCO_3$. Ind. J. Agric. Sci. **42.** 1095-1098.

OVCHARENKO, M. N. et al., 1974. On the transformation of primary and secondary minerals in solonetz profiles in North Kasakhstan (In Russian). Trans.10th Int. Cong. Soil Sci., Moscow. **7.** 146-153.

POLYNOV, B. B., 1956. New trends in the study of weathering. (In Russian) Selected works. 353-364. Moscow.

SZABOLCS, I., 1961. Effect of Water Regulation and Irrigation on Soil-forming Processes in the Tisza Valley (In Hung.). Akadémiai Kiadó. Budapest.

SZABOLCS, I., 1979. Review of Research on Salt-Affected Soils. Natural Resources Research. XV. UNESCO. Paris.

SZABOLCS, I., 1989. Salt Affected Soils. CRC Press. Boca Raton, Florida. USA.

SZENDREI, G., 1977. Investigations on calcite and dolomite distribution in the soils of Kiskunság area. (In Hung.) Agrokémia és Talajtan. **26.** 1-18.