Vegetation, soil hydrophysical properties, and grazing relationships in saline-sodic soils of Central Argentina

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Cisneros, J. M., Cantero, J. J. and Cantero, A. 1999. **Vegetation, soil hydrophysical properties, and grazing relationships in saline-sodic soils of Central Argentina**. Can. J. Soil Sci. **79**: 399–409. Land use and grazing regime can influence the dynamic of soil water and salt in humid areas. In Central Argentina, more than 2×10^6 ha are subjected to either permanent or cyclical processes of land salinization, alkalinization, flooding and sedimentation. In this region, the natural vegetation is the principal resource on which most systems of animal production are based. The objective of this study was to evaluate the effects of plant cover and grazing over some hydrophysical properties of three saline-sodic soils (two Gleic Solonetz in duripan phase and one Mollic Solonetz in fragipan phase), within a catena sequence. The effects on bulk density, saturated hydraulic conductivity, infiltration runoff, superficial salt accumulation and soil salinity distribution were determined in both bare and covered soil conditions, inside and outside of grazing exclosures. The results showed increased bulk density of topsoil for bare conditions, while saturated hydraulic conductivity did not show significant differences. In soils without any cover, the infiltration decreased significantly. Consequently, the runoff coefficient and salinity were greater, as indicated by significant salt accumulation in the topsoil. The soil profile salinity was reduced as a function of exclosure time, showing a trend toward desalinization resulting from a combined effect of soil cover and changes in intensity of land use. A conceptual model of salt and water dynamics in the soil profile for the landscape scale is postulated. The role of vegetation in regulating water and salt movement in poorly drained areas is emphasised as a basis for the development of management strategies.

Key words: Saline and sodic soils, infiltration, runoff, grazing, exclosure, model

Cisneros, J. M., Cantero, J. J. et Cantero, A. 1999. **Effets du couvert végétal et du pâturage sur certaines propriétés hydrophysiques des sols halomorphes sodiques de l'Argentine centrale**. Can. J. Soil Sci. **79**: 399–409. Le mode d'utilisation et le régime de pâturage peuvent influer sur la cinétique de l'eau du sol et du sel dans les régions humides. Dans l'Argentine centrale, plus de 2 millions d'hectares sont exposés de façon permanente ou cyclique à des phases de salinisation, d'alcalinisation, de submergence et de sédimentation. Dans cette région, la végétation naturelle est la principale ressource fourragère pour la plupart des productions animales. Nous avons cherché à évaluer les effets du couvert végétal et du pâturage sur certaines propriétés hydrophysiques de trois sols halomorphes sodiques (deux Solonetz gléyifiés en phase duripan et un Solonetz mollique en phase fragipan groupés en chaîne. Les effets sur la densité apparente, sur la conductivité hydraulique à saturation, sur l'infiltration, sur le ruissellement, sur l'accumulation de sel en surface et sur la répartition de la salinité dans le sol étaient observés en sol nu et en sol couvert à l'intérieur et à l'extérieur de parcelles d'exclusion de pâturage. La densité apparente du sol de surface était plus élevée en régime de sol nu, mais il n'y avait pas de différence significative à cet égard pour ce qui est de la conductivité hydraulique à saturation. De même, en sol nu l'infiltration diminuait significativement. Par conséquent le coefficient de ruissellement et la salinité étaient plus élevés comme en fait foi l'accumulation significative de sel dans le sol de surface. Le degré de salinité du profil diminuait en fonction de la durée d'exclusion de pâturage, révélant une tendance à la désalinisation sous l'effet combiné du couvert du sol et de la moindre intensité d'utilisation du terrain. Nous proposons un modèle conceptuel de la cinétique du sol et de l'eau dans le profil à l'échelle du paysage. L'importance du rôle de la végétation dans la régulation des mouvements de l'eau et du sol dans les zones mal drainées est mise en évidence, dans une perspective d'élaboration des stratégies de gestion du sol et du couvert végétale.

Mots clés: Sols salins et sodiques, infiltration, ruissellement, pâturage, parcelle d'exclusion, modèle

In central Argentina, the soil degradation process due to salinization, sodification, flooding and sedimentation, involves more than 2.2×10^6 ha (Gorgas and Lovera 1988; Instituto Nacional de Tecnología Agropecuaria 1990). These processes occur under different conditions of land use and management; however, few data are available on the water and salt dynamics in relation to the grazing regime. The increasing land area with low productivity due to salinization demands sustainable management strategies.

It is well known, according to the water and salt movement theory, that two conditions are needed for soil salinization to occur. First, soil must be in contact with a salt source and, second, salt accumulation processes must prevail either permanently or periodically over salt removal processes (Darab 1981). In this sense, the unfavourable hydrophysical conditions of salt-affected soils are the main limitation for primary productivity (Varallyay 1981). Much research has been conducted to characterize the influence of salt and Na on **saturated hydraulic conductivity** (**K**) (Varallyay and Mironenko 1979; Chawla et al. 1983), **non-saturated hydraulic conductivity** (**k**) (Bloemen 1981; Chang et al. 1986) and **infiltration rate** (**IR**) (Bresler et al. 1982; Shainberg and Letey 1984). Studies of K and IR lead to a quantification of the downward water movement, and

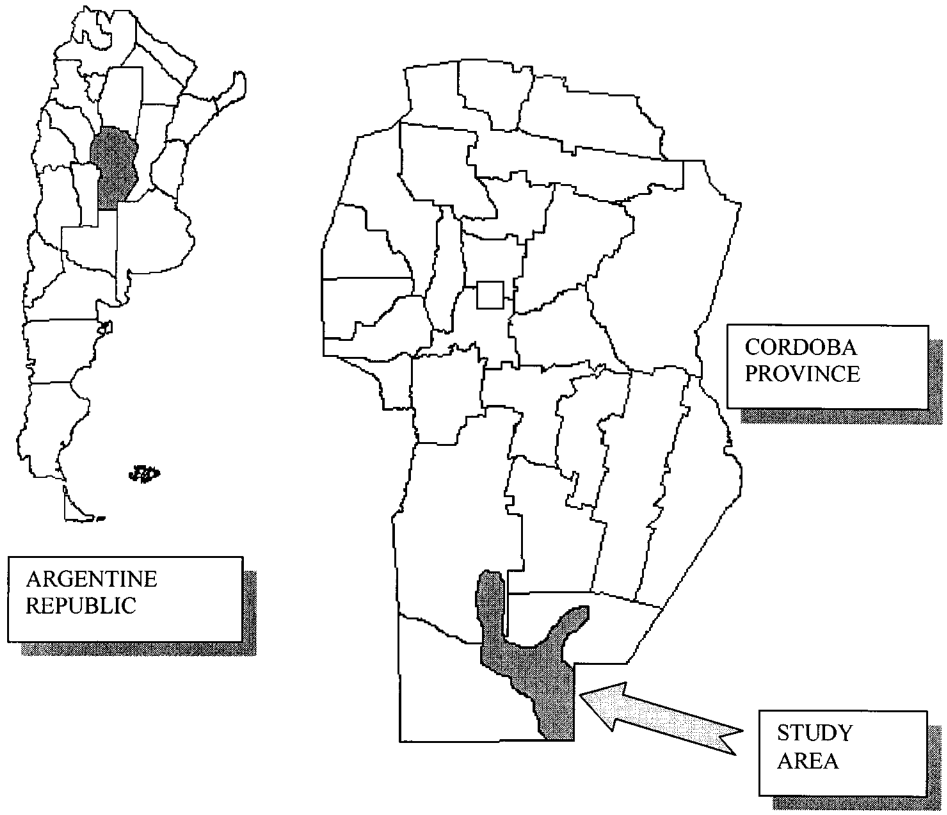

Fig. 1. Location of study area in Central Argentina.

those of nonsaturated k identify the upward water and salt upward capillary flows. The introduction of vegetation as a modifying variable of hydrological flow equilibrium has not been studied under saline conditions, even though its importance is well recognised in other form of soil degradation (Styczen and Morgan 1995).

The objective of this study was to characterize the effects of plant covers and grazing on some hydrophysical properties of some saline-sodic soils in Central Argentina. Specific objectives were: 1) to analyse the relationships between plant cover and grazing exclosures on the hydrophysical behaviour of soil, and 2) to propose a mechanism capable of explaining the tendencies in the salt migration-accumulation in the soil profile and among associated soil profiles.

MATERIALS AND METHODS

Study Area

The study area is located in the Southeastern quadrant of Córdoba province (Central Argentine), between 33° 20′ and 34°20′ South and 63°10′ and 64°00′ West (Fig. 1).

The climate is temperate, and subhumid, with a mean annual rainfall of 725 mm (ranging from 400 to 1100 mm). Precipitation is concentrated in the spring-summer (80% occurring between October and April), resulting in a dry winter. The average annual temperature is 16°C, ranging between 8 and 23°C in winter and summer, respectively. The water balance shows a period of excess during the fall (February–April), in which general flooding of the area may occur, and two deficit periods (April–June and November–January). An equilibrium period of balance (from June to October) can be observed.

Geomorphologically, the studied area is an extensive plain covering nearly 65 000 km^2, characterised by an intense fluvial paleoactivity and by modern eolic episodes that have partially covered these forms, resulting in soils of complex genesis (Cantú and Degiovanni 1984). The general drainage is controlled by geological faults that cause the accumulation of surface water and the rise of groundwater (WT) to near the soil surface. In this area, there are approximately 1400 permanent and semi-permanent salt lagoons, with different depths (40–200 cm) and salt contents (2–40 dS m^{-1}).

The soil texture varies accordingly to the type of geomorphological process; fluvial soils are either loam or clay loam, while eolian soils vary from sandy loam to sandy (Cisneros 1994).

The vegetation patterns are a function of the temporal and spatial geochemical dynamics of the landscape. The WT depth and the seasonal variation in salt content are the most important operational factors of the soil–plant system. The following plant communities have been identified within the study area (Cantero 1993): *Stipa trichotoma* + *S. tenuissima* + *S. papposa*, *Cynodon dactylon* + *Hordeum stenostachys*, *Distichlis scoparia*, *Atriplex undulata* + *Cyclolepis genistoides*, *Spartina densiflora*, *Distichlis spicata*, *Heterostachys ritteriana*, and *Sarcocornia perennis.*

Table 1. Some physical, chemical and morphological characteristics for the studied soils

Soil profile	FS[z]		SH		SM	
Soil horizon	A1	B21nag	A1	B21nag	A1	B21na1
Organic Matter (g kg^{-1})	23	9	17	12	23	2
pH, soil / water, 1 : 2.5	8.9	7.1	7.4	7.6	8.3	8.6
Clay, 0–2 µm (%)	17.6	22.9	17.5	22.2	19.2	21.8
Silt, 2–50 µm (%)	38.8	40.2	34.9	34.9	30.6	41.6
Sand, 50–2000 µm (%)	43.6	36.9	47.6	42.9	50.2	36.6
CEC (cmol$_c$ kg^{-1})	16.5	22.6	20.5	22.1	13.2	21.7
ESP (%)[y]	63.9	47.9	61.8	36.6	19.5	14.2
SAR	124.0	64.9	113.7	41.1	17.7	12.4
Duripan (0-60 cm)	Yes		Yes		No	
Fragipan (0-60 cm)	No		No		Yes	

[z]B21nag = B natric gley horizon, FS = footslope soil, SH = shoulder soil, SM = summit soil, CEC = cationic exchange capacity, ESP = exchangeable sodium percent, SAR = sodium adsorption ratio.
[y]Estimated from SAR-ESP relation (Bresler et al. 1982).

Soils Description

The study encompassed three contrasting environmental sites, which represent the heterogeneity of the study area. In each site, one soil profile called **footslope** (**FS**) (Ruhe and Walker 1968), **shoulder** (**SH**) and summit (**SM**), respectively, were studied. The three soil profiles, associated with different topographic position s along a catena, were separated from each other by approximately 500 m. Some physical and chemical characteristics of principal horizons of studied soils are shown in Table 1.

Soil profiles FS (footslope and toeslope). This soil profile is located on the lower side and at the base of the catena. The soil has a sandy loam texture, showing continual cementation starting at 37 cm depth, and is classified as Gleic Solonetz in duripan phase (Food and Agriculture Organization 1988). Precipitation and runoff water floods this soil for 30–60 d a year. The average WT depth during the study period was 46 cm (ranging from 1 to 110 cm), with a mean **electrical conductivity** (**EC**) of 22 dS m^{-1}. The vegetation is represented by the communities of *Distichlis spicata* and *Spartina densiflora*. The physical and morphological characteristics of profile are the following:

A1 0–14 cm; very dark brownish (10YR 3/2) in humid, loam, platy structure in the upper 2 cm (bare soil), in vegetated soil subangular blocky structure, hard, friable, slightly plastic and slightly sticky.
B21nag 14–29 cm; dark brown (10YR 3/3) in humid, loam, medium prismatic structure, slightly hard, slightly, friable, slightly plastic, sticky, fine clayskins and many red mottles.
B22nag 29–37 cm; dark yellowish brown (10YR 4,5/4) in humid, loam, medium and fine prismatic structure, hard, very firm, plastic, sticky, fine clayskins and many red and yellow mottles.
B31gm 37–46 cm; yellowish brown (10YR 5/4) in humid, massive structure, very hard, extremely firm, continue duripan with many mottles.
B32gx 46–58 cm; dark yellowish brown (10YR 4/4) in humid, sandy loam, medium prismatic and angular blocky structure, hard, firm, slightly plastic, nonsticky, fragipan, without carbonate reaction, many red and yellow mottles.
C + 58 cm; yelowish brown (10YR 4,5/4) in humid, sandy loam; fine, weak angular blocky structure, soft, friable, slightly plastic, nonsticky. Weak carbonate reaction, many red mottles.

Soil SH (shoulder): This soil profile is located on an intermediate plain. The soil is closely related to the previous profile, resulting from the same original material, but in this case the duripan development has been more intense, the soil is also classified as Gleic Solonetz in duripan phase. The average WT depth was 51 cm (ranging 12–120), the mean EC of the groundwater was 31 dS m^{-1}. The predominant vegetation is represented by the community of *Atriplex undulata* + *Cyclolepis genistoides*. The physical and morphological characteristics of profile are the following:

A1 0–6 cm; very dark grayish brown (10YR 3/2) in humid, sandy loam, very coarse platy structure, hard, friable to firm, nonplastic, slightly sticky, very compacted horizon, with saline crust in bare soil.
A2 6–15 cm; very dark grayish brown (10YR 3/2) in humid, sandy loam to loam, medium angular blocky structure, hard, friable, slightly plastic, slightly sticky, many red and yellow mottles.
B21nag 15–26 cm; dark brown (10YR 3/3) in humid, loam; medium weak prismatic structure, slightly hard, friable, slightly plastic, sticky. Many roots in anaerobic decomposition, fine clayskins, many red mottles.
B22nag 26–38 cm; yellowish brown (10YR 5/4) in humid, loam, fine prismatic structure, very hard, very firm. Saline crust in the lower boundary or horizon and between the aggregates.
B3m 38–79 cm; dark yellowish brown (10YR 4/4) in humid, massive, extremely hard, extremely firm. Clayskins and carbonate reaction in the soil mass.
C + 79 cm; brown (7,5YR 5/4) in dry, massive, extremely hard, extremely firm.

Soil SM (summit). This soil profile is located on an intermediate-high plain, within a smooth relief. The originating material of the soil is sandy loam, showing a fragipan development at 1 m depth, the soils is classified as Mollic

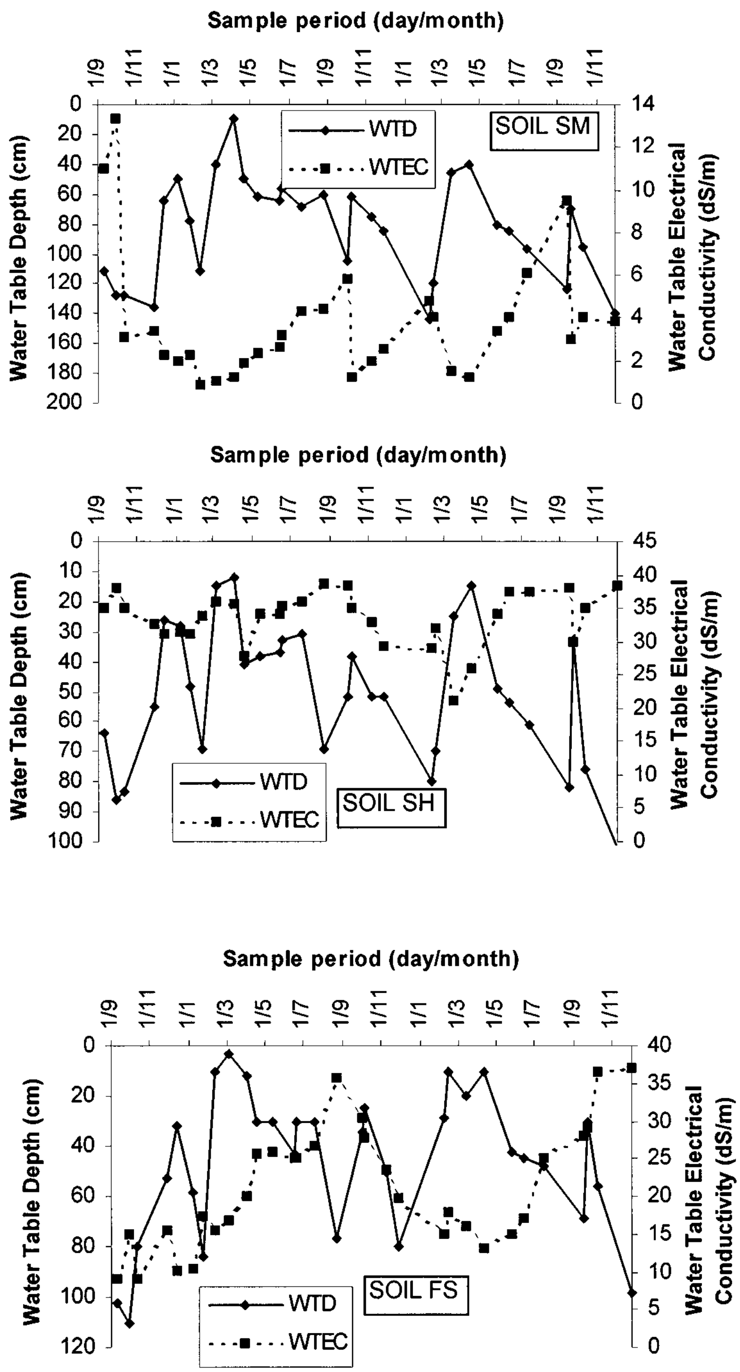

Fig. 2. Water table depths and electrical conductivity of the three soil profiles in the sampling period.

Solonetz in fragipan phase. The WT fluctuated around 82 cm (ranging 10–143 cm), and the groundwater exhibited a mean salinity of 4 dS m^{-1}. The community of *Cynodon dactylon* predominate. The physical and morphological characteristics of profile are the following:

A1 0–14 cm, dark grayish brown (10YR 4/2) in humid, sandy loam, medium moderate subangular blocky structure, hard, friable, nonplastic, slightly sticky, many roots and rhizomes of *Cynodon dactylon.*

A2 14–28 cm, dark grayish brown (10YR 4/2) in humid, loam, medium moderate subangular blocky structure, slightly hard, friable, nonplastic, nonsticky. Weak red mottles.

B21na 28–37 cm, brown (10YR 4/3) in humid, loam; coarse medium prismatic structure, slightly hard, friable, slightly plastic, sticky, weak clayskins and red mottles.

B22nax 37–60 cm, dark yellowish brown (10YR 4/4) in humid, loam to silty loam; coarse and medium prismatic structure, hard, firm, many clayskins and red mottles. Fragipan.

Table 2. Soil bulk density and K variations in relation to surface condition for the three soil profiles at two depths

	FS		SH		SM	
Sample layer (cm)	B[z]	C	B	C	B	C
			Bulk density, (Mg m^{-3})			
0 - 8	1.44	1.40*	1.56	1.33**	1.41	1.34*
8 - 16	1.25	1.24	1.24	1.29	1.41	1.34
			Satured hydraulic conductivity, (mm h^{-1})			
0 - 8	3.2	3.4	9.8	23.9*	3.0	16.9*
8 - 16	0.5	1.4	31.7	19.7	31.3	36.9

[z]B = bare/grazed soil profile, C = covered/ungrazed soil profile.
*, ** Significances between B and C at $P \leq 0.05$ and $P \leq 0.01$ respectively.

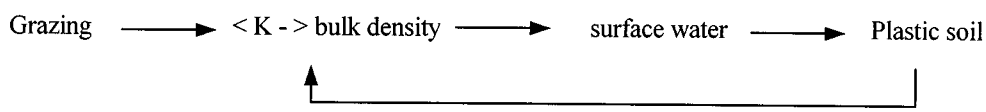

Fig. 3. Feedback loop between the grazing/trampling and the changes in hydrophysical/mechanical properties of topsoil.

B3g + de 60 cm; dark yellowish brown (10YR 4,5/4) in humid, sandy loam, coarse prismatic structure, hard, firm, many red mottles. Weak carbonate reaction between the aggregates. Friable calcium carbonate concretions.

Sampling and Determination of Soil Hydrophysical Properties

The trials were conducted on production plots. Exclosures to grazing of nearly 2000 m^2 were set for each type of soil on the selected plots. Samples of covered, non-grazed soil were taken from the exclosured areas since at the time of collecting samples there were no denuded situations observed. The sampling of bare/grazed soil outside the exclosures was performed under the same conditions used for the exclosures. Sampling was conducted on those patches showing no vegetation that define the maximum possible alteration of the grassland.

To evaluate the effect of land use, grazing exclosures consisting of both bare and covered soil (approximately 2000 m^2) were designed, in which the observations on plant cover were performed. In the area subjected to grazing, soil samples were taken in bare soil areas (saline patches).

In each sampling site, the **water table depth** (**WTD**) and **water table electrical conductivity** (**WTEC**) were monitored every month in one PVC observation hole of 7.5 cm diameter (Pizarro 1978). Rainfall was recorded with pluviometers located in the sampling sites, and potential evapotranspiration was estimated by the Thornwaite method (Taylor and Aschroft 1972).

The correlation between WTD and WTEC was taken as a direct measurement of the degree of salt dilution of the WT by rainwater, and as an indirect measurement of the internal drainage conditions of the soil (Cisneros 1994). The relationship between the rise of WT and the decrease of salt content is a measure of the dilution grade of WT and the rainfall proportion reaching the WT. The greater the rainfall ("distilled water") percolate, the more diluted the water table will be, especially under well-drained soil conditions. The soil salinity at each horizon below the WT was evaluated by **EC of saturation extracts** (**EC$_{se}$**) (Richards 1973) every other 2 mo, in both bare and covered soil. The salinity of the entire soil profile was evaluated by EC$_{se}$ weighted average for each soil horizon depth, down to the WT, accordingly to the following formula:

$$\text{EC weighted} = \Sigma\, \text{EC}_i \times \text{Depth}_i/\text{Total Depth}$$

Where EC weighted = soil EC weighted average (dS m^{-1}), EC$_i$ = EC$_{se}$ of the horizon i (dS m^{-1}), Depth$_i$ = horizon$_i$ width (cm) and Total Depth = total soil depth down to the WT (average of all samples).

In the upper 16 cm of soil, bulk density and K were determined by the cylinder method (Richards 1973), with three replications for each soil profile, soil depth and cover condition.

The IR curves and the runoff coefficients (runoff × 100/rainfall) were determined with a 1-m2 rainfall simulator (Marelli et al. 1986), taking three replicates for each surface condition. The intensities varied between 40 and 60 mm h–1, for 1 h of rainfall. In each infiltration trial, runoff samples were collected and their EC was measured.

Statistical Analysis

The statistical comparisons between variables cover/ungrazed vs. bare/grazed were done by a test of average differences with different variance (t´ test, Snedecor and Cochran 1984). All sampling was done by triplicate, standard deviations were calculated from mean values, and are shown as bars in Figs. 4, 5 and 6.

Information Synthesis

The results of soil and hydrogeological processes were synthesised in conceptual models of simple causal relationships, utilising the feedback theory of system approaches

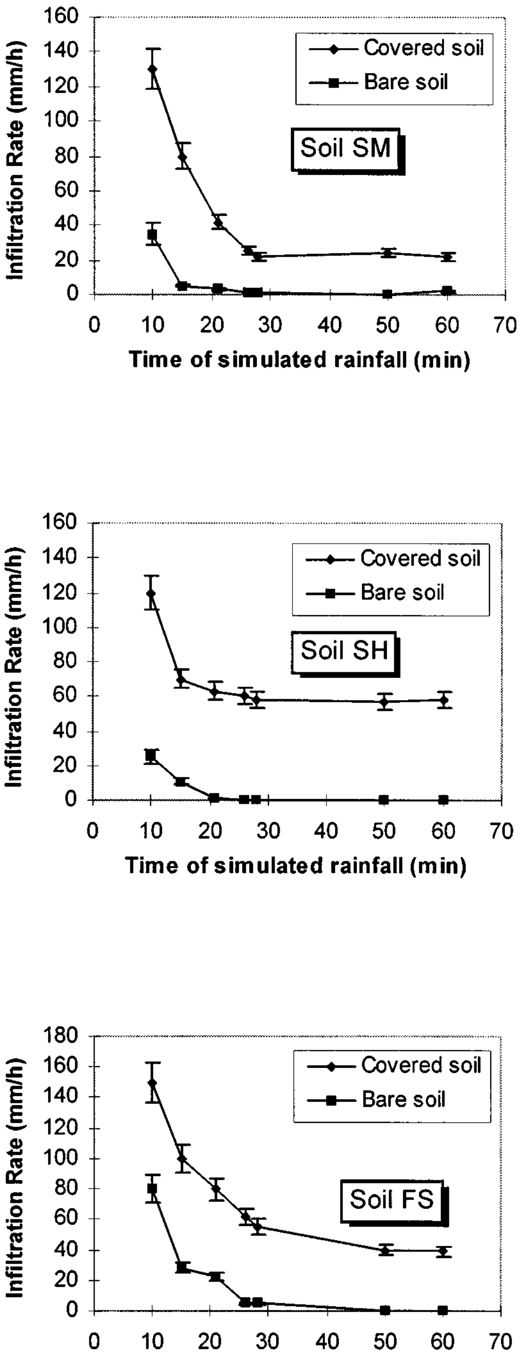

Fig. 4. Infiltration rates for the three soil profiles for both covered and bare soil.

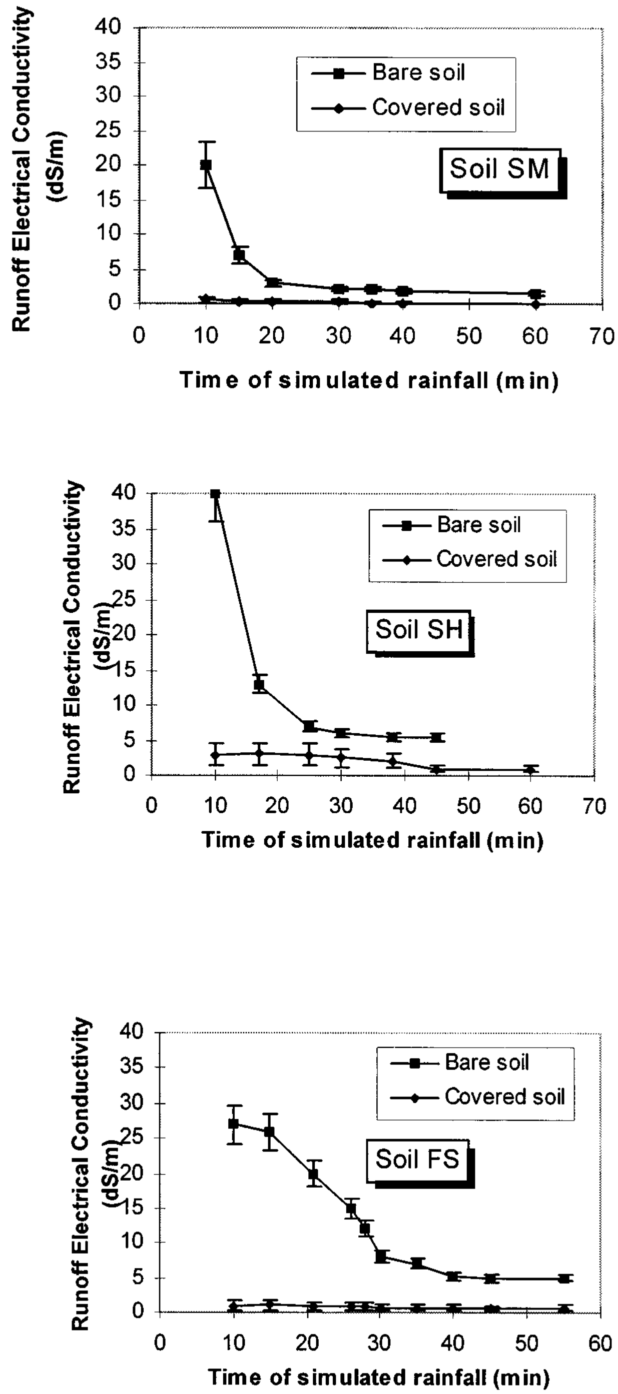

Fig. 5. Variations in runoff salinity for the three soil profiles for both covered and bare soil.

(Chen and Phien 1983). On a higher level of integration using all the obtained information, a conceptual model of water and salt movement and accumulation in the soil was postulated, derived from vectorial representations that indicate the principal flow magnitudes and directions and allow the principal landscape geochemical channels to be highlighted (Kozlovski 1972; Kovacs 1978; Varallyay 1981).

RESULTS AND DISCUSSION

Soil Water Table Dynamics

The WTD was closely related to the rainfall/evapotranspiration balance (Fig. 2). The WTEC dynamics for the studied soils were variable and they seem to be a function of the presence of a perched (local) water table. For example, this

Table 3 Runoff coefficients and runoff salinity variations as a function of surface condition for the three soil profiles

	Runoff coefficient (%)		Runoff salinity (g salt m^{-2} 50 mm of rainfall)[z]	
Soil	Covered/ungrazed	Bare/grazed	Covered/ungrazed	Bare/grazed
FS	34	80	1.6	270.5
SH	37	96	24.2	349.3
SM	47	82	3.3	163.7
Average	42	90	9.0	184.3
t value	5.4**		3.14**	

[z]This unit indicates the amount of salts incorporated at runoff in 1 m^2 of soil surface, in each 50 mm of rainfall.
** $P \leq 0.01$.

Table 4. Soil saturation extracts EC variations with soil depth in relation to surface condition for the three soil profiles

		EC_{se} average of sampling period (dS m^{-1})[z]		
Soil	Horizon (cm)	Covered/ ungrazed	Bare/ grazed	*t* value
FS	0–2	26.1	53.6	**
	2–6	21.5	24.7	NS
	6–14	21.4	23.6	NS
	14–29	24.1	21.7	NS
	29–37	23.3	23.5	NS
	37–46	23.2	18.6	NS
SH	0–6	27.9	55.4	**
	6–15	28.1	28.0	NS
	15–26	23.7	24.0	NS
	26–38	26.6	24.7	NS
	38–50	27.5	25.1	NS
SM	0–5	5.8	41.2	**
	5–14	5.0	15.7	**
	14–28	7.1	14.3	**
	28–37	8.6	17.6	**
	37–47	8.7	17.8	**
	47–60	7.6	17.1	**

[z]Average values of EC_{SE} of five samples obtained between periods of 2 mo.
** $P \leq 0.01$, NS = non significant.

is shown in the SM soil in which the salinity values were lowest (Fig. 2). A perched water table is a body of water suspended over an impermeable layer, and is hydrologically disconnected from the regional WT; thus for this reason it has a low WTEC.

The WTD was always above the critical depth (i.e., WTD at which the topsoil salinization occur), with flooding periods occurring only in FS. The correlation WTD–WTEC was highly significant only in the SM profile ($r = 0.57$, $P \leq 0.01$), indicating a different hydrogeological dynamic from those of FS and SH. In the SU profile, the principal WT recharge resulted from rainfall and, from the low WTEC observed, was probably a perched WT. In contrast, the FS and SH soils, with highly saline groundwater, represented a situation in which the groundwater was regional and the recharge with saline runoff water was significant.

Soil Bulk Density and Saturated Hydraulic Conductivity

The results indicated that in bare and grazed soil, bulk density increased only in the topsoil (0–8 cm), for all of the soils analysed (Table 2). At the lower soil depth (8–16 cm), bulk density was similar among treatments. Similar results have been found by Taboada and Lavado (1988), but in finer textured soils.

As soil bulk density increased the soil K decreased, at 0–8 cm depth. This reduction in permeability would maintain rainwater for longer periods at the soil surface, so that the soil would remain in a plastic state while it is trampled. In coastal salt marshes, Webb et al. (1995) found that the waterlogging period was a principal factor in vegetation dieback. This would tend to deteriorate soil structure, generating a positive feedback loop towards topsoil compaction. This is schematically represented in Fig. 3.

Infiltration Rate – Runoff

The higher surface cover, for the soils in the exclosured sites, modified the IR curves compared with bare-trampling situations (Fig. 4). The sharp decreases in IR indicate a soil disaggregation effect and sealed surface, whose intensity is greater in bare soil. Other studies have suggested the existence of a superficial control of IR by crusting, especially in soils with high exchangeable Na (Gal et al. 1984; Agassi et al. 1985; Bosch and Onstad 1988). For all the cases of bare

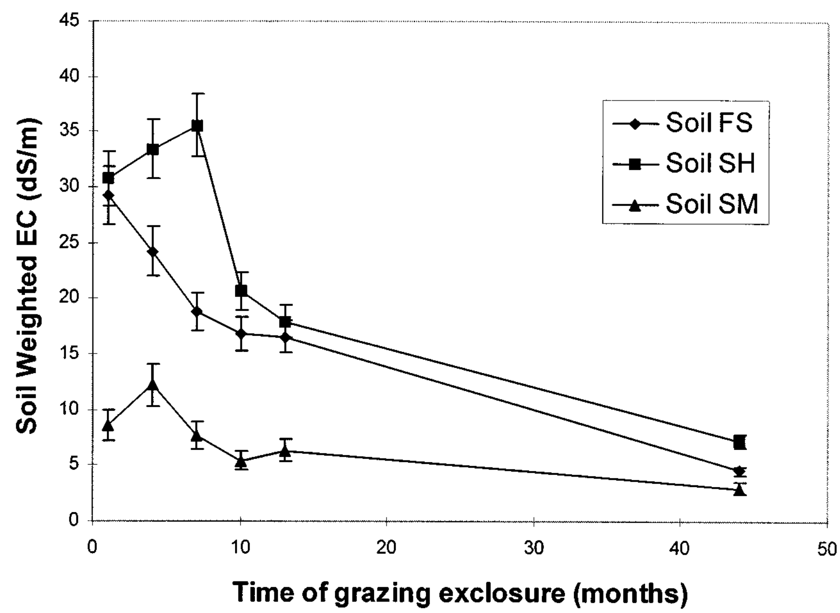

Fig. 6. Soil salinity for the total soil depth sampled, for the three soil profiles, during the exclosure period obtained by weighted average of EC_{se} of each horizon by its depth.

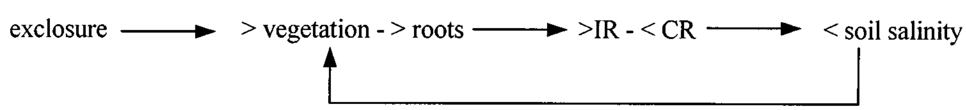

Fig. 7. Feedback loop between exclosure to grazing and increase in soil salinity due to vegetational changes.

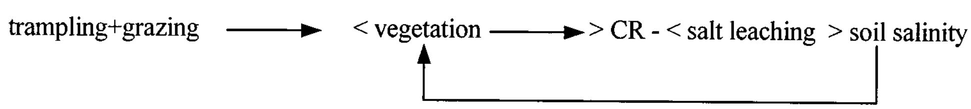

Fig. 8. Feedback loop between trampling and grazing and decrease in soil salinity by increased capillary rise due to the loss of vegetation.

soil studied, at the time of the simulated rain trial, the infiltration approached zero.

Covered soils within the area of exclosure increased the IR, retention and detention of water. Evolution of runoff salinity generated by simulated rainfall also showed contrasting behaviour between bare and cover soil (Fig. 5). These also reflected contrasting biogeochemical behaviour, in which the denudation of the surface increased the transfers of salt among the different components of the catena. The runoff coefficients (C, %) and the runoff salt concentration, expressed in g m^{-2} 50 mm^{-1} of rain, were strongly influenced by the soil surface condition (Table 3).

According to the US Department of Agriculture (1968) classification of soil in hydrological groups, the soils studied in bare condition belong to hydrologic group D (with a major runoff potential), with a Number Curve higher than 90. The same soils under cover belong to groups B or C, with a Number Curve between 40 and 70. In the first group, the effective rainfall (infiltrated rainfall) did not exceed 20%, while in the second group it could reach 77%, and was never less than 30% (Table 3).

Soil Salt Accumulation

SHORT-TERM (1-YR) VEGETATION EFFECTS. Salt concentration in a specific soil volume and at a certain time is the result of a complex process of addition, transportation and accumulation of water and salt flows (Sokolenko 1984). This balance is structurally governed by topographic position, climatic condition, WTD and hydrophysical characteristics of the soil. Functionally, the presence or absence of vegetation mainly regulates the accumulation sites, the velocities and direction of the flows.

The results showed a clear tendency toward surface salt concentration in those sites without vegetation; this higher accumulation, in some cases, was significant to a depth of 10 cm (Table 4). Toth et al. (1995) and Kreeb et al. (1995) found a high correlation between salinization/alkalinization

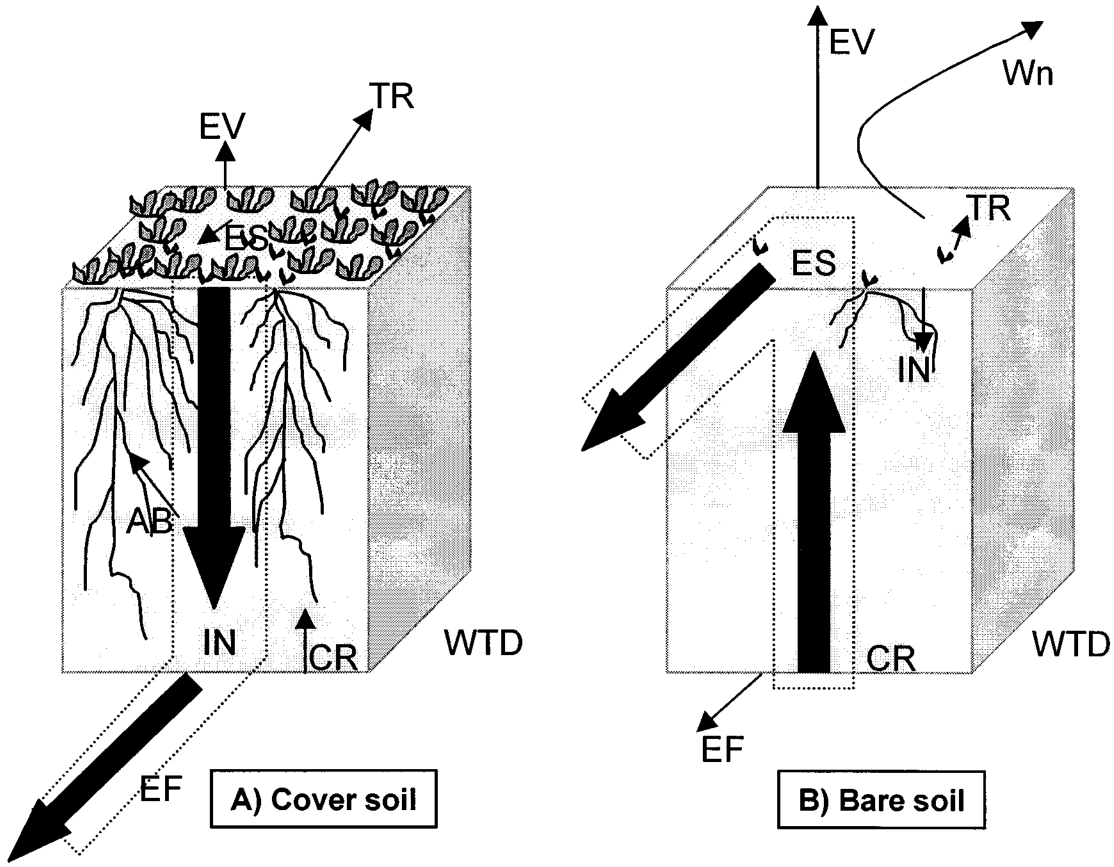

Fig. 9. Diagrammatic representation of humid area salt-affected soils hydrogeochemical functional types. TR = water transpiration, EV = soil water evaporation, ES = water and salt surface runoff, AB = water absorption by roots, EF = drainage, CR = water and salt movement by capillary rise, IN = soil water infiltration, Wn = salt movement by wind, WTD = water table depth. The principal soil geochemical channels, are given by dotted lines.

in bare topsoil and soil coverage percent due to grazing effect.

Below the surface, soil salinity is governed by the WTEC, for both covered and bare soil. In covered soil, the salinity of the 0- to 5-cm soil depth tends to be similar to or less than that of the corresponding WT. These differences in salt surface accumulation indicate a change in the flow equilibrium, especially between capillary rise/infiltration (CR/IR). For bare soil, CR would clearly predominate over IR, as the high values of ECes and the decrease in K and IR indicate. These results explain the differences found in the salinity of the surface runoff (Table 3).

The soil cover modifies the surface energy balance, reducing the thermic gradient between the soil and the atmosphere, however, vegetation cover results in higher plant transpiration, which will reduce the velocity of the capillary flow when k decreases due to the effect of soil drying at a greater depth . The relationship between k and soil moisture has been widely studied in soils with no vegetation (Varallyay and Mironenko 1979; Hillel 1980), but little is known about the specific effects of root systems on this relationship.

MIDTERM (5-YEARS) VEGETATION AND NON-GRAZING EFFECTS. In the case of sites without grazing, the tendency of soil profiles exposed for the short term is to a progressive desalinization of the soil (Fig 6). The results indicate that, with vegetation development and a decrease in trampling-grazing, the balance CR/IR tends to favour a predominance of IR. Thus, the existence of a new feedback loop is postulated, which would equilibrate the salinity of the soil profile to a minimum, without the influence of grazing according to the flow diagram shown in Fig. 7.

In contrast, an excess of trampling-grazing will lead the system towards a maximum salinity in the soil profile and especially in the surface area, an effect that can be explained by another feedback loop like the one shown in Fig. 8.

These phenomena show that for some saline-sodic soils in seasonally humid climate conditions, a direct relationship between the increase of salinity and the improvement of K does not exist, as it does with the classical floculation-dispersion equilibrium. In these cases, where the natural vegetation acts as a stabilizing factor, desalinization allows an increase in K and IR. This fact is clear in bare soil, in which the increase of salinity does not imply flocculation or an increase in K. This could be associated wth the fact that an irreversible dispersion of colloidal material operates in those soils in which coarse fractions predominate.

The soil surface, as it is the critical site for germination, sprouting and establishment of halophyte species, defines the direction of the process. Mahmood et al. (1994) found that topsoil salinity controlled halophyte seed germintation. In covered soil, the progressive desalinization increases the probability of the establishment of the plant species; therefore, in each desalinization cycle (wet season) a change operates in the quali-quantitative composition of grassland or shrubland (Mahmood et al. 1994). The dilution of the soil solution permits a greater root development because of the smaller osmotic potential, which promotes better soil structuring and a greater number of water circulation channels, all of which feed back to the system again.

The dramatic effects of the plant cover on the surface soil salinity are also clearly reflected in other perception scales. Thus, in stands of some plant communities, such as in those of *Heterostachys ritteriana, Sarcocornia perennis* and *Distichlis spicata* microdomes of 0.5–1 m^2 (pedestals), which emerge in the form of small islands within the surrounding plain, are frequently found (Cantero 1993). The origin of these microdomes is associated with the morphological architecture of the three dominant species cited: vegetative regeneration is the strategy of dominant perpetuation in these species and it is resolved through rhizomes and runners that grow in multiple directions, generally following a circular pattern. These are interceptors of surface flows and act as efficient sediment traps.

Information synthesis: Conceptual Model of the Soil–Water–Salt Dynamics

It is possible to postulate the existence of two functional dynamic types in saline-sodic soils influenced by the WT for subhumid, temperate areas (Fig. 9): a) Bare soil dynamic type and, b) Vegetated soil dynamic type

VEGETATED SOIL DYNAMIC TYPE. All the analysed soils demonstrated a significant tendency toward a reduction in their surface salinity due to plant cover effects. This tendency was accentuated in the communities closed to grazing. The IR increased with cover in a recurring way, which would explain the different salinization rhythms. In this dynamic type, the downward vertical flows (infiltration, percolation) and horizontal underground flows (EF runoff and eventually hypodermic flow) predominated, in a positive feedback loop leading to salt leaching. On a landscape scale, this dynamic type would generate different soil hydromorphic conditions (fresh depressions), in which the EF suffers high dilution. This was considered a flow equilibrium whose stability depends on the maintenance of the cover and on controlling the grazing, without which a change toward another dynamic type is highly possible.

BARE SOIL DYNAMIC TYPE. The main characteristics of this model were the surface accumulation of salt and Na and high saline runoff values, with a predominance of upward-vertical flows (capillary rise, evaporation) and horizontal-surface flows (runoff). This dynamic will lead to the system possessing more prolonged and saline lagoon formations in the lower topographical positions. So, the bare soils tend to increase flooding due to local runoffs, which will be faster, more prolonged and show higher salinity levels. Following the same criteria, the predominance of soils with plant cover would decrease the locally flooded areas as a result of the slowing down of the flow, the increase in retained water in the soils and the plant use. Srivastava and Jefferies (1996), explained the desertification process in arctic saltmarshes by a similar positive feedback between grazing, halophyte growing and soil salinity.

CONCLUSIONS

Vegetation modified the hydrophysical properties of saline-sodic soils, especially the infiltration velocity and the capillary flow of salt toward the surface. In the upper first centimetres, covered soils tended to maintain a salinity level similar or inferior to that of the WT, while bare soils tended to be concentrated in ratios of up to 10:1 with respect to the WTEC.

Besides being the basic productive resource of the region, the natural vegetation operated as a regulator of local flooding events, which are due to surface runoffs. Soil management techniques should be orientated toward maintaining or achieving total surface cover as well as improving the hydrophysical conditions of the topsoil.

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Agassi, M., Morin, J. and Shainberg I. 1985. Effect of raindrop impact energy and water salinity on infiltration rates of sodic soils. Soil Sci. Soc. Am. J. **49**: 186–190.

Bloemen, G. W. 1981. Calculation of steady state capillary rise from the groundwater table in multi-layered soil profiles. Tech. Bull. 121 ICW Wageningen, The Netherlands. pp. 701–719.

Bosch, D. D. and Onstad C. A. 1988. Surface seal hydraulic conductivity as affected by rainfall. Trans. ASAE **31**(4): 1120–1127.

Bresler, E., Mc Neal, B. L. and Carter, D. L. 1982. Saline and sodic soils. Principles – dynamics – modelling. Springer Verlag, Berlin, Germany. 236 pp.

Cantero, J. J. 1993. La vegetación y su relación con factores ambientales en paisajes hidrohalomórficos. Magister Scientiae Thesis. Buenos Aires National University, Buenos Aires, Argentina.

Cantú, M. P. and Degiovanni S. 1984. Geomorfología de la región centro-sur de la provincia de Córdoba. IX Congreso Geológico Argentino. Actas IV: 76-92. San Carlos de Bariloche.

Chang, C., Sommerfeldt, T. G., Schaalje, G. B. and Palmer, C. J. 1986. Effect of subsoiling on wheat yield and salt distribution of a Solonetzic soil. Can. J. Soil Sci. **66**: 437–443.

Chawla, K. L., Khosla B. L. and Sharma, D. R. 1983. Hydraulic properties of a sandy loam soil as influence by salinisation and desalinisation. Irrig. Sci. **4**: 247–254.

Chen, L. G. and Phien, H. N. 1983. Dynamo quality modelling for the Hsintien River, Taiwan. Water SA **9**(1): 9–22.

Cisneros, J. M. 1994. Characterization of hydrohalomorphism in typical environments of centre-south area of Córdoba (Argentina). Magister Scientiae Thesis. Buenos Aires National University, Buenos Aires, Argentina.

Darab, K. 1981. The role of sodium compounds in the formation and properties of salt affected soils. Agrokem. Talajtan Suppl. **30**: 105–120.

Food and Agriculture Organization. 1988. FAO/UNESCO: Soil map of the world. Revised legend. World Resources Report 60. FAO, Rome, Italy.

Gal, M., Arcan, L., Shainberg, I. and Keren, R. 1984. Effect of exchangeable sodium and phosphogypsumon crust structure — Scanning electron microscope (SEM) observations. Soil Sci. Soc. Am. J. **48**: 872–878.

Gorgas J. and Lovera, D. 1988. Evaluación de areas afectadas por anegamiento e inundación en la Provincia de Córdoba. Convenio Fundación Banco de Cordoba-INTA.

Hillel, D. 1980. Fundamentals of soil physics. Academic Press, Inc., New York, NY. 407 pp.

Instituto Nacional de Tecnología Agropecuaria. 1990. Atlas de Suelo de la Republica Argentina. Provincia de Cordoba. Escala 1:500.000.

Kovacs, G. 1978. Hydrology and water control on large plains. Hydrol. Sci. **23**(3): 305–332.

Kozlovski, F. 1972. Structural functional and mathematical model of migrational landscapes geochemical process. Soviet Soil Sci **4**(2): 228–243.

Kreeb, K. H., Walley, R. D. B. and Charley, J. L. 1995. Some investigations into soil and vegetation relationships associated with alkaline-saline soil surfaces in the Walcha Area, Northern Tablelands, New South Wales. Aust. J. Agric. Res. **46**(1): 209–224.

Mahmood, K., Malik, K. A., Lodhi, M. A. K. and Sheikh, K. H. 1994. Soil–plant relationships in saline wastelands – vegetation, soils, and successional changes, during biological amelioration. Environ. Conserv. **21**(3): 236–241.

Marelli, H. J., Arce, J. M. and Masiero, B. 1986. Simulador de lluvias para investigación básica en conservación de suelos. Publicación Técnica No 8, Serie Suelos y Agroclimatología. INTA Marcos Juarez.

Pizarro, F. 1978. Drenaje agrícola y recuperación de suelos salinos. Editorial AgrÌcola Española S. A. 521 pp.

Richards. L. (Ed.). 1973. Rehabilitación de Suelos Salinos y Sódicos. Ed. Limusa, Mexico.

Ruhe, R and Walker, P.H. 1968. Hillslope models and soil formation. Open Systems. Trans. 9th Int. Conf. Soil Sci. , IV. 246 pp.

Shainberg, I. and Letey, J. 1984. Response of soils to sodic and saline conditions. Hilgardia **52**(2): 1–57.

Snedecor, G. W. and Cochran, W. G. 1984. Métodos estadísticos. Compañía Editorial Continental S. A. 703 pp.

Sokolenko, V. 1984. Water and salt regimes of soil: Modelling and management. A. A. Balkema, Rotterdam, The Netherlands.

Srivastava D. S. and Jefferies, R. L. 1996. A possitive feedback ñ herbivory, plant growth, salinity and the desertification of an arctic salt-marsh. J Ecol. **84**(1): 31–42.

Styczen M. E. and Morgan, R. P. C. 1995. Engineering properties of vegetation. *In* R. P. C Morgan and R. J. Rickson, eds. Slope stabilization and erosion control: A bioengineering approach. E. and FN Spon, London, UK.

Taboada, M. A. and Lavado, R. S. 1988. Grazing effects of the bulk density in a Natraquoll of the Flooding Pampa of Argentina. J. Range Manage. **41**: 500–503.

Taylor, S. and Ashcroft, G. 1972. Physical edaphology. W. H. Freeman and Co., San Francisco, CA. 533 pp.

Toth, T., Matsumoto, S., Mao, R. H. and Yin, Y. F. 1995. Precision of predicting soil salinity based on vegetation categories of abandoned lands. Soil Sci. **160**(3): 218–231.

US Department of Agricluture, Soil Conservation Service. 1968. A method for estimating volume and rate of runoff in small watershed. USDA, Washington, DC. TP 149.

Varallyay, G. and Mironenko, E. V. 1979. Soil water relationships in saline and alkali conditions. Agrokem. Talajtan Suppl. **28**: 33–82.

Varallyay, G. 1981. Extreme moisture regime as the main limiting factor of the fertility of salt affected soils. Agrokem. Talajtan Suppl. **30**: 73–96.

Webb, E. C., Mendelssohn, I. A. and Wilsey, B. J. 1995. Causes for vegetation dieback in a Louisiana salt marsh – a bioassay approach Aquat. Bot. **51**(3–4): 281–289.