Advances in the prognosis of soil sodicity under dryland and irrigated conditions

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Abstract

Salt-affected soils, both saline and sodic, may develop under both dryland and irrigated conditions, affecting the physical and chemical soil properties, with negative consequences in the environment, in crop production and in animal and human health. Among the development processes of salt-affected soils, the processes of sodification have generally received less attention and are less understood than the development of saline soils. Although in both, hydrological processes are involved in their development, in the case of sodic soils we have to consider some additional chemical and physicochemical reactions, making more difficult their modeling and prediction. This is especially true where we have to consider the effects of the groundwater level and composition. In this contribution there are presented three case studies: one related to the development of sodic soils in the lowlands of the Argentina Pampas, under dry-land conditions with sub-humid temperate climate and pastures for cattle production; the second deals with the development of sodic soils in the Colombia Cauca Valley, under irrigated conditions and tropical sub-humid climate, in lands used for sugarcane cropping dedicated to sugar and ethanol production; and the last one related to the sodification of soils in the Western Plains of Venezuela, under irrigated conditions, sub-humid tropical climate and continuous cropping of rice under flooding. The development of sodicity in the surface soil is partially related to the composition and level of the ground-water, mainly affected in the Argentina case by drainage conditions, in the case of Colombia to the inefficient irrigation and inadequate drainage, and in the case of Venezuela to the soil management and irrigation system. There is shown how the model SALSODIMAR, developed by the author, based on the balance of water and soluble components of both irrigation water and ground-water, under different water and land management conditions, may be successfully adapted for the diagnosis and prediction of the different processes and problems, and for selection of alternatives for their prevention and amelioration.

Key Words: Sodicitiy, Models, Hydrology, Ground water

1 Introduction

Salinization and sodification are the main processes of soil degradation affecting irrigated lands. The growing development of irrigated agriculture is necessary for the sustainable production of the food required by the increasing World's population. Such development is limited by the increasing scarcity and low quality of available water resources and by competitive use of those resources for other purposes. There are also increasing problems of contamination by irrigated lands drainage effluents to surface and ground waters.

Irrigated agriculture makes a major contribution to the world's food supply. The degradation of irrigated lands through soil salinization and sodification becomes very important from the economic, social and environmental points of view. Besides, large and increasing proportions of the World's irrigated land (25%–50% depending on the evaluations) are affected by excessive salinity and sodicity.

In general, the soil salinity problems are a consequence of salt accumulation in zones and depths where the soil moisture regime is characterized by strong losses of water by evaporation and transpiration, and by reduced leaching of the remaining salts. The soil sodicity problems appear as a consequence of changes in the

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composition and concentration of those salts, with changes in the equilibrium exchangeable cations, leading to higher relative accumulation of exchangeable sodium percentage (ESP). Both processes of salinization and sodification are therefore influenced by soil water and solute balances (Pla, 1997).

Irrigation and drainage may cause drastic changes in the regime and balance of salts and sodium in the soil profile, resulting in problems of salinization or sodification depending on climate, crops, soils, ground-water depth, irrigation and ground-water composition, and irrigation and drainage management. Restricted drainage may be due to low permeability of the soil or to the presence of shallow ground water. Furthermore, the drainage waters coming from irrigated lands may contain not only natural salts, but also residues of fertilizers and pesticides, which are generally used in large amounts in intensive irrigated agriculture, and other pollutants derived from animal wastes and composted materials used as amendments and from partially or non-treated urban or industrial waste-waters increasingly being used for irrigation. The most important sustainability constraints associated with irrigation by waste-waters, besides potential contamination by pathogens and heavy metals, are due to salinity and sodicity (Pereira et al., 2009). Problems of soil sodicity are the more common potential alterations to be considered when treated sewage effluents are used for irrigation (Halliwell et al., 2001).

2 Development and properties of sodic soils

Salt-affected soils, both saline and sodic, may develop under both dryland and irrigated conditions (Fig. 1). Among the development processes of salt-affected soils, the processes of sodification have generally received less attention and are less understood than the development of saline soils. Hydrological processes are involved in both developments, but in the case of sodic soils we have to consider some additional chemical and physicochemical reactions, making more difficult their modeling and prediction.
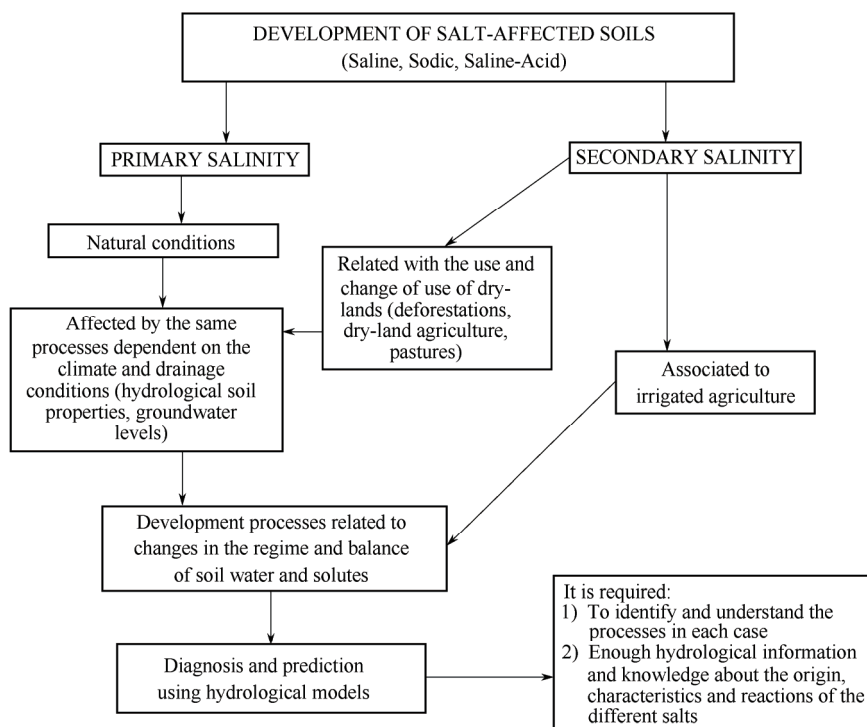

Fig. 1   Common factors in the development of salt-affected soils under dryland and irrigated conditions

Sodic soils are dominated by Na (and by Mg in some cases) on their cation exchange sites. The sodicity status in the soil is expressed by the Sodium Adsorption Ratio (SAR) (United States Department of Agriculture, 1954):

$$SAR = Na / [(Ca + Mg)/2]^{1/2} \quad (meq/liter)^{1/2} \tag{1}$$

or by the ESP, both related to each other. We prefer and recommend the use of SAR for practical reasons (ESP is very difficult to measure correctly in most sodic soils), and because our experience in many sodic soils, under very different conditions, makes it even a more reliable index of sodicity than ESP. Depending on different factors, soils are considered sodic if the ESP is 5%–40%. The general lack of understanding of sodicity is in part due to the considerable variation of sodicity definitions, with variable ESP (or SAR) values reported to pose a sodicity problem, due to different textures and mineralogy of the soils and lack of consideration of the accompanying soil solution electrolyte concentration.

Sodicity produces changes in the soil's physical properties, both by dispersion and plugging of soil pores by the moving clay particles and soil pore blockage by swelling clays. When surface soil disperses, the clay and silt particles clog surface pores, resulting in soil sealing, reduced infiltration and surface water-logging. This affects land use and plant growth by decreasing the permeability of water and air through the derived soil water-logging, and impeding root penetration. These mechanisms are affected by several soil factors, mainly texture, clay mineralogy, total salinity and pH (Rengasamy & Olson, 1991). Dispersion affects more soils with illite and kaolinite clays, at very low values of SAR if the salinity levels are also low, while swelling effects are more common in soils with smectites. Exchangeable Mg enhances dispersion from sodicity (Keren, 1991), but to a greater extent in illitic soils than in smectite soils (García, 2002; Madero et al., 2004). It has been stated (Rengasamy & Sumner. 1998; Rengasamy & Marchuk, 2011) that there is a need to derive and define a new ratio of these cations in place of SAR, called "Cations Ratio of Soil Structural Stability" (CROSS) which will indicate the separate effects of Na, K, Mg and Ca on soil structural stability. This could be achieved using a formula analogous to the SAR:

$$CROSS = (Na + 0.56K)/[(Ca + 0.6\,Mg)/2]^{1/2} \quad (meq/liter)^{1/2} \qquad (2)$$

SAR$_{SE}$ values (Na$^+$/(Ca^{++} + Mg^{++})$^{1/2}$ (mmoles/liter)$^{1/2}$) with increasing salt concentration (C$_{SE}$ meq/liter) in soil saturation extract (SE) from an origin al water with 5 meq/liter of salts (2.5 meq/liter Na$^+$; 1.25 meq/liter Ca^{++}; 1.25 meq/liter Mg^{++}) and different anion composition and concentrations (Cl: Chlorides; S: Sulphates; B: Bicarbonates) (CA: Ca + Mg; K: Saturated soil hydraulic conductivity)
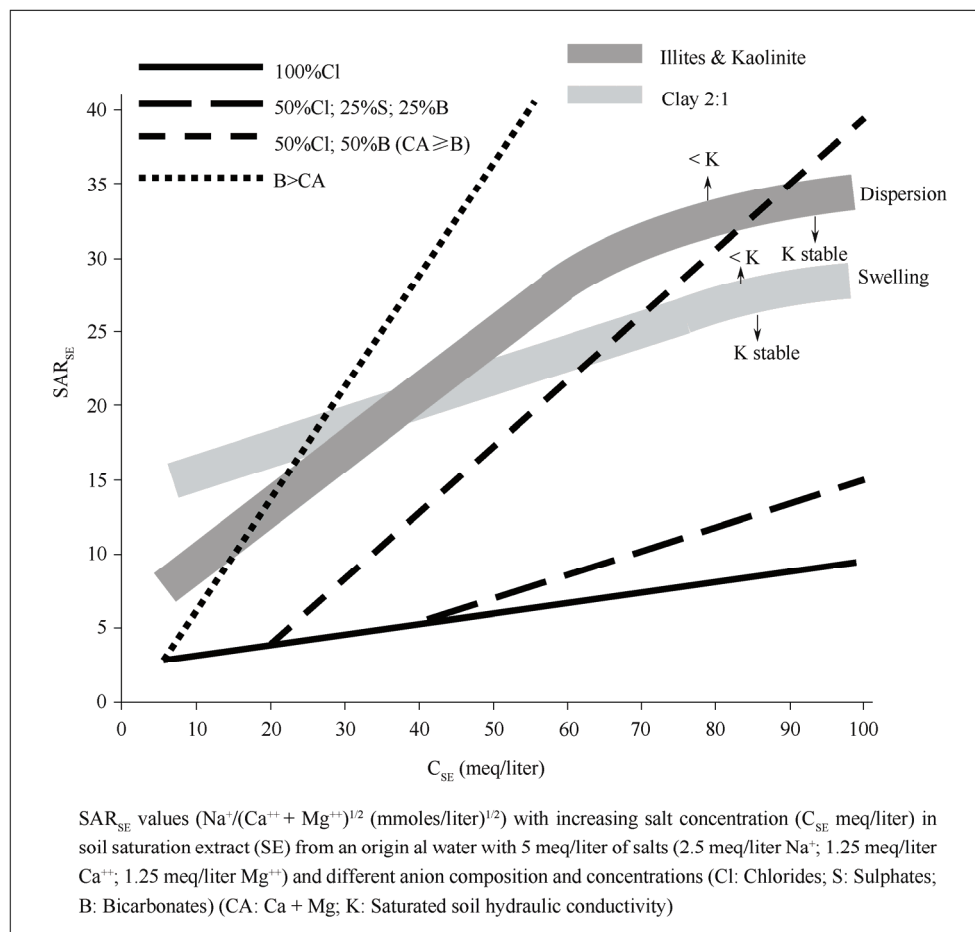
Fig. 2   Relationships between salinity and sodicity in the soil solution, and their effects on clay dispersion or swelling and in the soil hydraulic conductivity, for different anionic composition of the original water and different soil clays

The relationship between soil salinity and its flocculating effects, and sodicity and its dispersive or swelling effects on soil physical properties, especially the ones related to soil infiltration rates and hydraulic conductivity, is required to predict how specific soils will behave under different predicted combinations of salinity(C_{SE}) and sodicity (SAR_{SE}) (Fig. 2). Those relationships, reported by Quirk and Scofield (1955) and by Reeve (1960), depend highly on clay type, soil chemical reactions and soil texture (Frenkel et al., 1978; Oster & Shainberg, 2001). Among the main soil chemical reactions affecting those salinity/sodicity relationships are the ones involving bicarbonates and carbonates of Ca, Mg and Na, and Ca sulphates, leading to salt precipitation or dissolution, with changes in the soil salinity and sodicity levels (Pla, 1967, 1998). Many errors in the evaluation and prediction of sodicity problems and effects are due to the non correct consideration of those chemical reactions under different relations among those cations and anions (Fig. 2). The main mistakes are not considering the effects of sodium bicarbonate accumulation in soil solution, which comes from irrigation waters or ground-waters, or is produced by reactions under anaerobic conditions as shown in Fig. 4.

3 Prognosis of soil sodification

Both the addition of irrigation water and the changes in the depth and composition of ground water may cause drastic changes in the water and solute balances in the soil profile. Modeling may be very useful for the diagnosis and prediction of such changes, and in the selection of the best practices and systems of irrigation and drainage for a more efficient use of irrigation water and for reducing the losses and contamination of surface and ground water, and controlling the soil salinization and sodification.

Use of more saline and sodic irrigation waters, such as treated municipal waste-waters and irrigation drainage waters, can be expected to increase in the future. This will require modification of existing soil and crop management practices, with consideration of the interaction between soil management and soil sodicity under different levels of salinity. The main final objective has to be increased production with less water, reducing and controlling at the same time the negative environmental impacts on surface and ground-waters. Current available computer models provide only a limited ability to predict correctly those impacts of salinity and sodicity under different management conditions. It is necessary to include in computer models the interaction of many physical and chemical processes, for predicting short and long term consequences of varied management practices (Suárez, 2005).

Most of the present concepts and approaches (static water quality indices, fixed limits for soil salinity and sodicity critical levels, are empirical predictive models based on statistical relations or in laboratory methods not reflecting field conditions), although they can characterize a particular system, they are only applicable to the conditions under which they were developed.They are not reliable if extrapolated to different situations. Model predictions would have to incorporate the effect of both the soil chemical (solution and exchange composition) changes, and soil and water management, as a function of irrigation and ground-water composition; and also the balance of water and solutes in the soil as influenced by climate, irrigation system, ground-water depth and crop water uptake to be suitable. The model requirements are particularly important for soil sodification, where to reach an equilibrium level of exchangeable sodium may take a long time (up to several decades) to occur, but the resulting effects are very difficult to reverse.

A modeling approach, understanding and based on hydrological processes and associated impacts, may assist with decision making, and may provide an ability to test the impact of a variety of remedial or preventive options difficult to test previously in the field. The model SOMORE (Pla, 1997, 2006) and their present version (Fig. 3) may be used for the initial evaluation of the soil water balances related to soil salinization and sodification processes. It has been found that vegetation changes can have strong effects on water dynamics, and on salt and sodium accumulation and distribution at different temporal and spatial scales under shallow ground-water. Therefore, hydrological studies, including water and salt balances, and water table fluctuation analysis, will be needed to preview the consequences of land use and vegetation changes on soil salinization and specially sodification processes, and to guide the requirements of irrigation and drainage management to prevent them.

The proposed model "SALSODIMAR" (Pla, 1968, 1988, 1997; Pla & Dappo, 1977) is based on an independent balance of the salts and ions common in irrigation waters, in ground-waters and in the soil solution The model also takes into consideration the processes and effects derived of the interaction among the

compositions of the irrigation and groundwater, evapotranspiration, reactions of solution, precipitation and cation exchange, the soil hydrological properties and the effective leaching fraction (Figs. 4 and 5). It was initially developed (Pla, 1967, 1968) to include the effect of hydrological aspects of irrigation and drainage on the salinization, and especially on the sodification processes in soils, associated to reactions of solution and precipitation of Ca and Mg carbonates and Ca sulphates occurring in the field. Subsequently, the effects of hydrological factors affecting the water and solute balances, the soil characteristics and the irrigation management were included in the model (Pla, 1983, 1986; Pla & Dappo, 1977), and all was programmed in EXCEL for practical use. As such, it has been successfully used and tested at different levels, under tropical, subtropical and Mediterranean climate conditions (De Paz et al., 2004; Guerrero et al., 2004, 2007; Madero et al., 2004; Pla, 1972, 1985, 1986, 1988, 2006; Ramírez, 2012; Ramirez et al., 2014; Sánchez et al., 2014; Vargas, 2001).
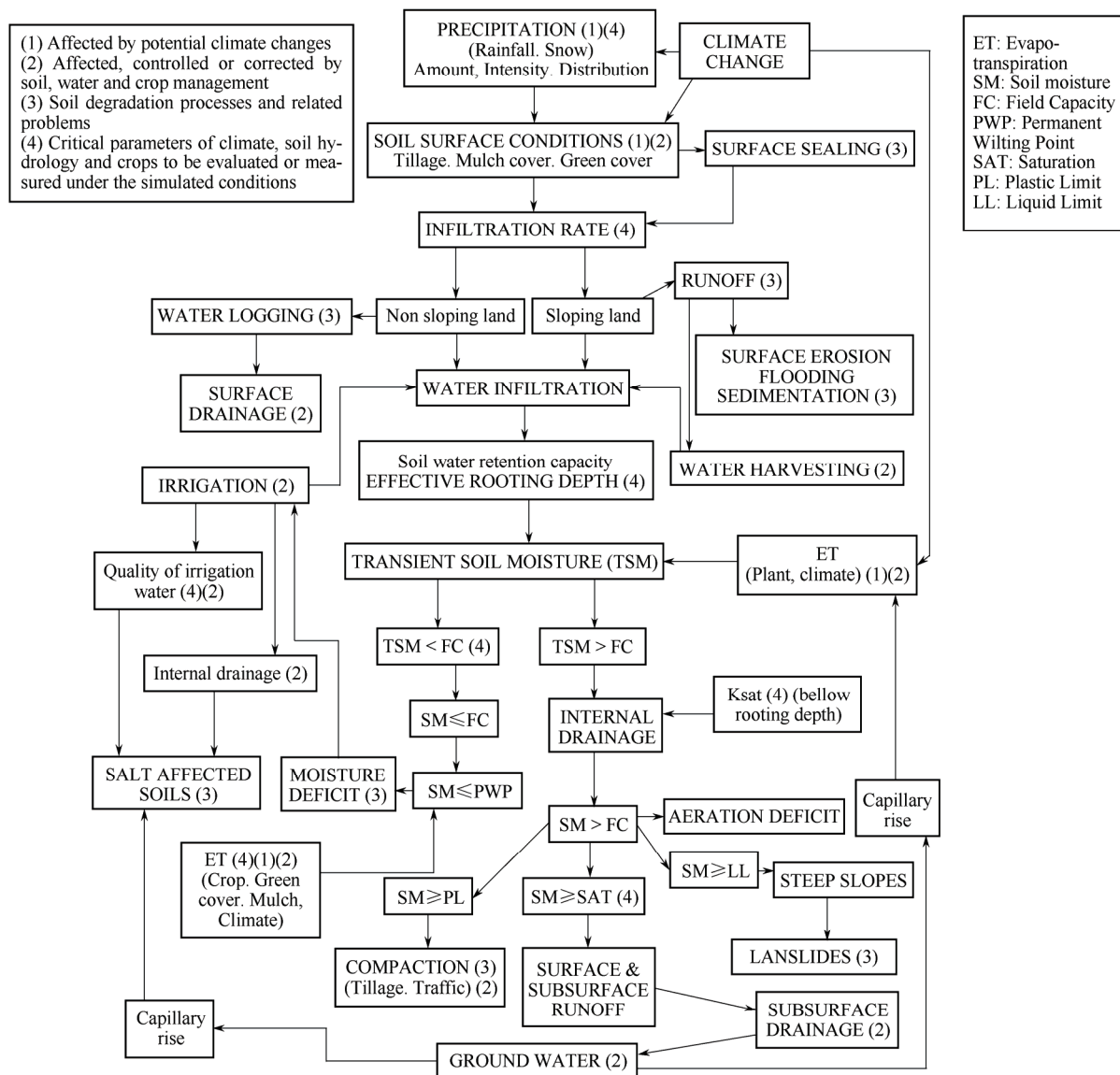
Fig. 3   Flow diagram of the present version of the soil water balance model SOMORE (adapted from Pla, 1997, 2006)

In this paper there is presented an adaptation of the model SALSODIMAR, including new specific hydrological components of the water and solute balances, to make it useful to predict the processes of both the dryland salinization and sodification processes originated in the ground-water, and the combined effects of irrigation and ground-water, with or without vegetation (Figs. 5 and 6; Table 1).

WASTES → IRRIGATION WATER ← POLLUTANTS

Soil ← SEDIMENTS

Concentration of salts, ions and toxic elements (C)

Maximum allowed levels (C_{SE}) in soil solution
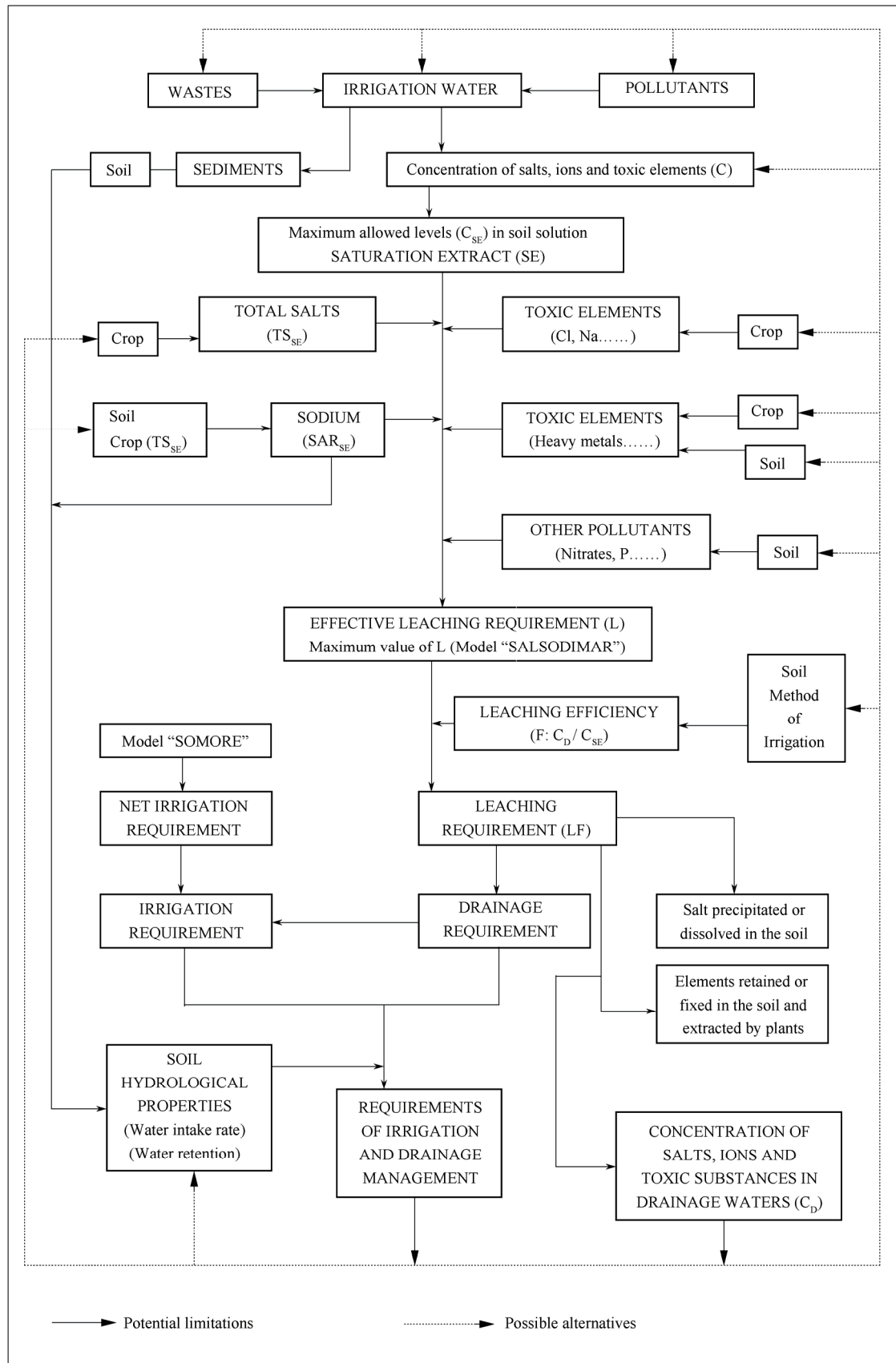SATURATION EXTRACT (SE)

Crop → TOTAL SALTS (TS_{SE}) → TOXIC ELEMENTS (Cl, Na......) ← Crop

Soil Crop (TS_{SE}) → SODIUM (SAR_{SE}) → TOXIC ELEMENTS (Heavy metals......) ← Crop
Soil

OTHER POLLUTANTS (Nitrates, P......) ← Soil

EFFECTIVE LEACHING REQUIREMENT (L)
Maximum value of L (Model "SALSODIMAR")

LEACHING EFFICIENCY (F: C_D/ C_{SE}) ← Soil Method of Irrigation

Model "SOMORE"

NET IRRIGATION REQUIREMENT

LEACHING REQUIREMENT (LF)

IRRIGATION REQUIREMENT ← DRAINAGE REQUIREMENT

Salt precipitated or dissolved in the soil

Elements retained or fixed in the soil and extracted by plants

SOIL HYDROLOGICAL PROPERTIES (Water intake rate) (Water retention)

REQUIREMENTS OF IRRIGATION AND DRAINAGE MANAGEMENT

CONCENTRATION OF SALTS, IONS AND TOXIC SUBSTANCES IN DRAINAGE WATERS (C_D)

→ Potential limitations   ┄┄► Possible alternatives

Fig. 4   Flow diagram of a conceptual model of a balance of salts and toxic substances in irrigated soils
[SAR: Sodium Adsorption Ratio = $Na+/[(Ca^{++}+ Mg^{++})/2)]^{1/2}$ $(meq/liter)^{1/2}$]
(Model "SOMORE": Pla, 2006; Model "SALSODIMAR": Pla, 1997)

Conditions

IRRIGATION WATER OR GROUNDWATER

Concentration:	(High)	(Medium)	(Low)	
EC	>2dS/m	1-2 dS/m	<1dS/m	
Composition	Cl>S>B	S≥Cl>B	B≥S>Cl	B>S>Cl (B<CA)
	Na ≥CA	CA>Na	CA>Na	Na≥CA

DRAINAGE

	(Variable)	(Very restricted)	(Restricted)
Soil Perm (I)	1-50 mm/hour	< 1mm/hour	< 5mm/hour
Groundwater depth#	< 1,5 m	< 0,5 m	< 1,0 m

CLIMATE

	(Ar.-DSAr.)	(Ar.-DSAr.)	(DSAr.-SH.)	(Ar.-HSAr.)
IMA (P/ETP)	< 0,5	< 0,5	0,5-1,0	< 0,8
LGP (P>(ETP/2))	< 120 days	< 120 days	120-270 days	<180 days

Resulting problem

SOIL SOLUTION (SE)

	(Very Saline)	(Mod. Saline)	(Sligh. Saline)	(Var. Salinity)
Concentration (EC)	> 8 dS/m	> 4 dS/m	< 4 dS/m	> 2 dS/m
Composition	Cl>>S>>B	Cl≥S>>B	S>Cl>B	S≥B>Cl (*) ·······▶ B≥S>Cl
	Na>CA	Na≥CA	Na>CA	Na>>CA Na>>CA
pH	< 8,5	< 8,5	> 7,5	> 8,5
PRECIP. SALTS	CAC + CaS	CAC + CaS	CAC	CAC

POTENTIAL PROBLEM	**SALINITY**	**SODICITY**

(*) Change in composition under anaerobic conditions ($2Na^+ + SO_4^= + 2C + 2H_2O = S^= + 2NaHCO_3$)
Permanent groundwater depth or presence of soil layers restricting internal drainage.
Depths for medium to fine texture soils. May be shallower for coarse texture soils.

Fig. 5 More common conditions leading to the development of different kinds of saline and sodic soils applying the model SALSODIMAR (Pla, 1997) (EC: Electrical Conductivity; Cl: Chlorides; S: Sulphates; B: Bicarbonates; CA: Calcium + Magnesium; CAC: Ca+Mg Carbonates; CaS: Calcium Sulphate; SE: Saturation Extract; I: Infiltration Rate; P: Rainfall; ETP: Potential Evapo-Transpiration; Ar: Arid Climate; DSAr: Dry Semi-Arid Climate; SH: Sub-Humid Climate; HSAr: Humid Semi-Arid Climate)

Table 1(a)   Equations to calculate the water and salt balances in the surface soil to predict salinization and sodification processes under different conditions, including the effects of ground water, irrigation, and soil cover

BARE SOIL (NO IRRIGATION)

$H_G = H_E - H_P$ (If : $H_E - H_P \geq 0$) ; $L_G = H_P / (H_E - H_P)$

At equilibrium: **If : $CA_G \geq B_G$**

If: $CAB_G / L_G \geq 10$ and $CaS_G / L_G \geq 30$

$CA_{SE} = ((CA_G - CAB_G - CaS_G) / L_G) + 40$; $Na_{SE} = Na_G / L_G$

$CAC_p = (CAB_G / L_G) - 10$; $CaS_p = (CaS_G / L_G) - 30$

If: $CAB_G / L_G \geq 10$ and $CaS_G / L_G < 30$

$CA_{SE} = ((CA_G - CAB_G) / L_G) + 10$; $Na_{SE} = Na_G / L_G$

$CAC_p = (CAB_G / L_G) - 10$

If: $CAB_G / L_G < 10$ and $CaS_G / L_G < 30$

$CA_{SE} = CA_G) / L_G$; $Na_{SE} = Na_G / L_G$

If : $CA_G < B_G$

$CA_{SE} = CA_G$; $Na_{SE} = Na_G / L_G$

$CAC_p = (CAB_G / L_G) - CA_G$

$C_{SE} = CA_{SE} + Na_{SE}$

$SAR_{SE} = Na_{SE} / (CA_{SE} / 2)^{1/2}$

SOIL COVER WITH VEGETATION (NO IRRIGATION)

$H_G = H_{ET} - H_T - H_P$ (If : $H_{ET} - H_T - H_P \geq 0$) ;

$L_G = H_P / (H_E - H_T - H_P)$

At equilibrium: **If : $CA_G \geq B_G$**

If: $CAB_G / L_G \geq 10$ and $CaS_G / L_G \geq 30$

$CA_{SE} = ((CA_G - CAB_G - CaS_G) / L_G) + 40$; $Na_{SE} = Na_G / L_G$

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$CAC_p = (CAB_G / L_G) - 10$

If: $CAB_G / L_G < 10$ and $CaS_G / L_G < 30$

$CA_{SE} = CA_G) / L_G$; $Na_{SE} = Na_G / L_G$

If : $CA_G < B_G$

$CA_{SE} = CA_G$; $Na_{SE} = Na_G / L_G$

$CAC_p = (CAB_G / L_G) - CA_G$

$C_{SE} = CA_{SE} + Na_{SE}$

$SAR_{SE} = Na_{SE} / (CA_{SE} / 2)^{1/2}$

H_G: Water coming from the water table, reaching the surface soil by capillary rise (mm)

H_E : Water loss by potential evaporation in a bare soil surface (mm)

H_{ET} : Water loss by potential evapo-transpiration in a soil surface covered with vegetation (mm)

H_T : Water loss by transpiration of the vegetation or crop covering the soil surface (mm)

H_P : Effective rainfall (infiltrated in situ) (mm)

H_R : Water applied by irrigation (mm)

C_G : Salt concentration in the ground-water (meq/liter)

C_R : Salt concentration in the irrigation water (meq/liter)

C_D : Salt concentration in the drainage water (meq/liter)

C_{SE}: Salt concentration in the saturation extract of the surface soil (meq/liter)

SAR : Sodium Adsorption Ratio (Na / (CA/2)$^{1/2}$) (meq/liter)$^{1/2}$

SE: Saturation extract of the soil

E: Leaching efficiency

G : Ground-water

CA: $Ca^{++} + Mg^{++}$ (meq/liter)

Na: Na^+ (meq/liter)

B: HCO_3^- (meq/liter)

S : $SO_4^=$ (meq/liter)

CAB = CA if B ≥ CA

CAB = B if B < CA

CaS = Ca – B – CACl if CaS ≥ 0 and (CaCl = Ca –B –S if CaCl ≥0)

CAC_p : Precipitated (Ca + Mg) carbonates (meq/liter)

CaS_p: Precipitated Ca sulphates (gypsum) (meq/liter)

Not shown are cases where $H_E - H_P < 0$ (NO COVER) or $H_{ET} - H_T - H_P < 0$ (VEGETATION COVER), and the only surface water input is rainfall water (NO IRRIGATION), because no soil salinization or sodification problems would be expected in such cases, unless the ground water table reaches the surface soil.

Table 1(b)   Equations to calculate the water and salt balances in the surface soil to predict

salinization and sodification processes under different conditions, including

the effects of ground water, irrigation, and soil cover

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SOIL COVER WITH VEGETATION (IRRIGATION)
(NET UPWARD FLOW)

$H_G = H_{ET} - H_T - H_P - H_R$ (If : $H_{ET} - H_T - H_P - H_R \geq 0$) ;

$L_G = (H_P + H_R)/(H_E - H_T - H_P - H_R)$

At equilibrium: **If : CA$_G \geq$ B$_G$**

If: $CAB_G / L_G \geq 10$ and $CaS_G / L_G \geq 30$

$CA_{SE} = ((CA_G - CAB_G - CaS_G)/L_G) + 40$; $Na_{SE} = Na_G / L_G$

$CAC_p = (CAB_G / L_G) - 10$; $CaS_p = (CaS_G / L_G) - 30$

If: $CAB_G / L_G \geq 10$ and $CaS_G / L_G < 30$

$CA_{SE} = ((CA_G - CAB_G)/L_G) + 10$; $Na_{SE} = Na_G / L_G$

$CAC_p = (CAB_G / L_G) - 10$

If: $CAB_G / L_G < 10$ and $CaS_G / L_G < 30$

$CA_{SE} = CA_G)/L_G$; $Na_{SE} = Na_G / L_G$

                  If : CA$_G <$ B$_G$

$CA_{SE} = CA_G$; $Na_{SE} = Na_G / L_G$

$CAC_p = (CAB_G / L_G) - CA_G$

$C_{SE} = CA_{SE} + Na_{SE}$

$SAR_{SE} = Na_{SE} / (CA_{SE} / 2)^{1/2}$

(NET DOWNWARD FLOW)

If : $H_{ET} - H_T - H_P - H_R < 0$

$H_D = H_P + H_R - H_{ET}$; $L_D = (H_P + H_R - H_{ET})/H_R$

At equilibrium: **If : CA$_R \geq$ B$_R$**

If: $CAB_R / L_D E \geq 10$ and $CaS_R / L_D E \geq 30$

$CA_{SE} = ((CA_R - CAB_R - CaS_R)/L_D E) + 40$; $Na_{SE} = Na_R / L_D E$

$CAC_p = (CAB_R / L_D E) - 10$; $CaS_p = (CaS_R / L_D E) - 30$

If: $CAB_R / L_D E \geq 10$ and $CaS_R / L_D E < 30$

$CA_{SE} = ((CA_R - CAB_R)/L_D E) + 10$; $Na_{SE} = Na_R / L_D E$

$CAC_p = (CAB_R / L_D E) - 10$

If: $CAB_R / L_D E < 10$ and $CaS_R / L_D E < 30$

$CA_{SE} = CA_R)/L_D E$; $Na_{SE} = Na_R / L_D E$

                  If : CA$_R <$ B$_R$

$CA_{SE} = CA_R$; $Na_{SE} = Na_R / L_D E$

$CAC_p = (CAB_R / L_D E) - CA_R$

$C_{SE} = CA_{SE} + Na_{SE}$

$SAR_{SE} = Na_{SE} / (CA_{SE} / 2)^{1/2}$

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H_G: Water coming from the water table, reaching the surface soil by capillary rise (mm)

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S : SO$_4^=$ (meq/liter)

CAB = CA if B $\geq$ CA

CAB = B if B < CA

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CAC_p : Precipitated (Ca + Mg) carbonates (meq/liter)

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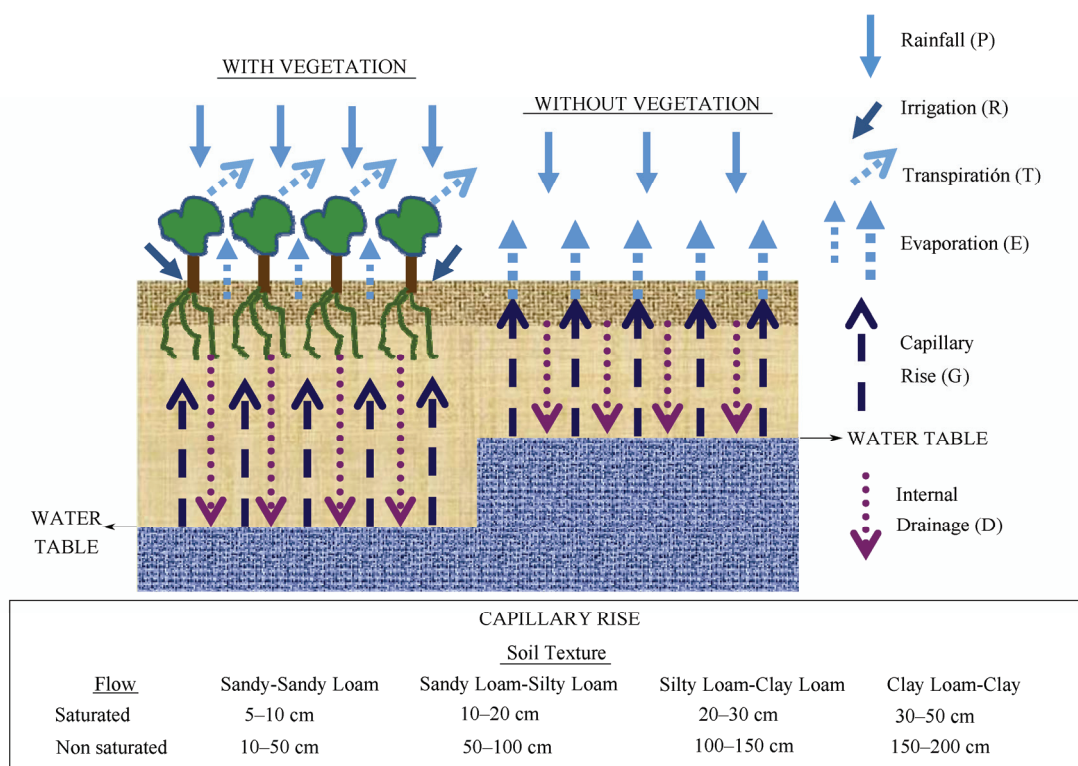
WITH VEGETATION

WITHOUT VEGETATION

Rainfall (P)

Irrigation (R)

Transpiratión (T)

Evaporation (E)

Capillary
Rise (G)

WATER TABLE

Internal
Drainage (D)

WATER
TABLE

WATER
TABLE

CAPILLARY RISE				
	Soil Texture			
Flow	Sandy-Sandy Loam	Sandy Loam-Silty Loam	Silty Loam-Clay Loam	Clay Loam-Clay
Saturated	5–10 cm	10–20 cm	20–30 cm	30–50 cm
Non saturated	10–50 cm	50–100 cm	100–150 cm	150–200 cm

**Fig. 6 Components of the water balance with the presence of shallow groundwater,
with or without vegetation cover**

4 Case studies

In this contribution there are presented three case studies (Fig. 7; Table 2). One related to the development of sodic soils in the lowlands of the **Argentina Pampa**, under dry land conditions and sub-humid temperate climate, with pastures for cattle production. The other deals with the development of sodic soils in the **Colombia Cauca Valley**, under irrigated conditions and tropical sub-humid climate, in lands used for sugarcane cropping dedicated to sugar and ethanol production. The last one is related to the development of sodic soils under mixed dry land-irrigated conditions for the production of rice in the **Western Plains of Venezuela**, with a dry sub-humid climate. In all cases the development of sodicity in the surface soil is mainly related to the effects of the composition and level of groundwater. In the **Argentina Pampa** it is affected by the off-site changes in dry land use and management in the upper zones and by the drainage conditions in the lowlands, and in the cases of the **Cauca Valley in Colombia** and **Western Plains in Venezuela** by the on-site irrigation and drainage management on lands with sugarcane and rice respectively.

The case in the Argentina Pampa (PAMPA) is located in the low lying, poorly drained lands of the Pampa region, with natural pastures for cattle production (Fig. 8). The drainage of excess water from the higher elevated areas of the Pampas (now with continuous soybean cropping) raise the water table in the lower lying areas. This water dissolves salts of geologic origin from the soil and underlying substrata. The mobilized and transported soluble salts accumulate and over time salinize the groundwater, with sodification of the surface soil in the areas where the water tables approach ground level. There are many barren areas or area with scarce natural pasture cover, due to degradation by overgrazing and soil salinization and sodification (Casas & Pittaluga, 1984, 1990).

The climate is temperate subhumid (Table 2), with a variable rainfall amount and distribution contributing to variable water table depths (60–160 cm), with flooding some years, and variable concentration and composition of the groundwater. For the simulation, an extinction depth (water table depth at which groundwater evaporation effectively ceases) of 60 cm was used, based on local experience for the silty loam soils. Recharge and discharge totals, month by month, were distributed according to climate conditions. In the area there are field experiments with the objective of reducing recharge of the groundwater and reclaiming the saline and sodic soils. The approach is to establish high water use, salt-tolerant and deep rooted perennial pastures, like

Agropirum elongatum (agropiro alargado), Lotus tenuis (lotus), Melilotus albus (trébol de olor blanco), Melilotus officinalis (trébol de olor Amarillo) and Chloris gayana (grama Rhodes) (Casas and Pittaluga, 1984). The expected beneficial effects of this kind of cover are: reduction in capillary flow from the water table to the soil surface, increased infiltration, and improvement of soil chemical and physical properties. Some of those effects in surface soil salinity and sodicity are shown in Table 3. Other engineering options for balancing recharge and discharge, such as mole and tile draining water tables or pumping groundwater have limitations due to cost, disposal of drained water and soil hydrological conditions.
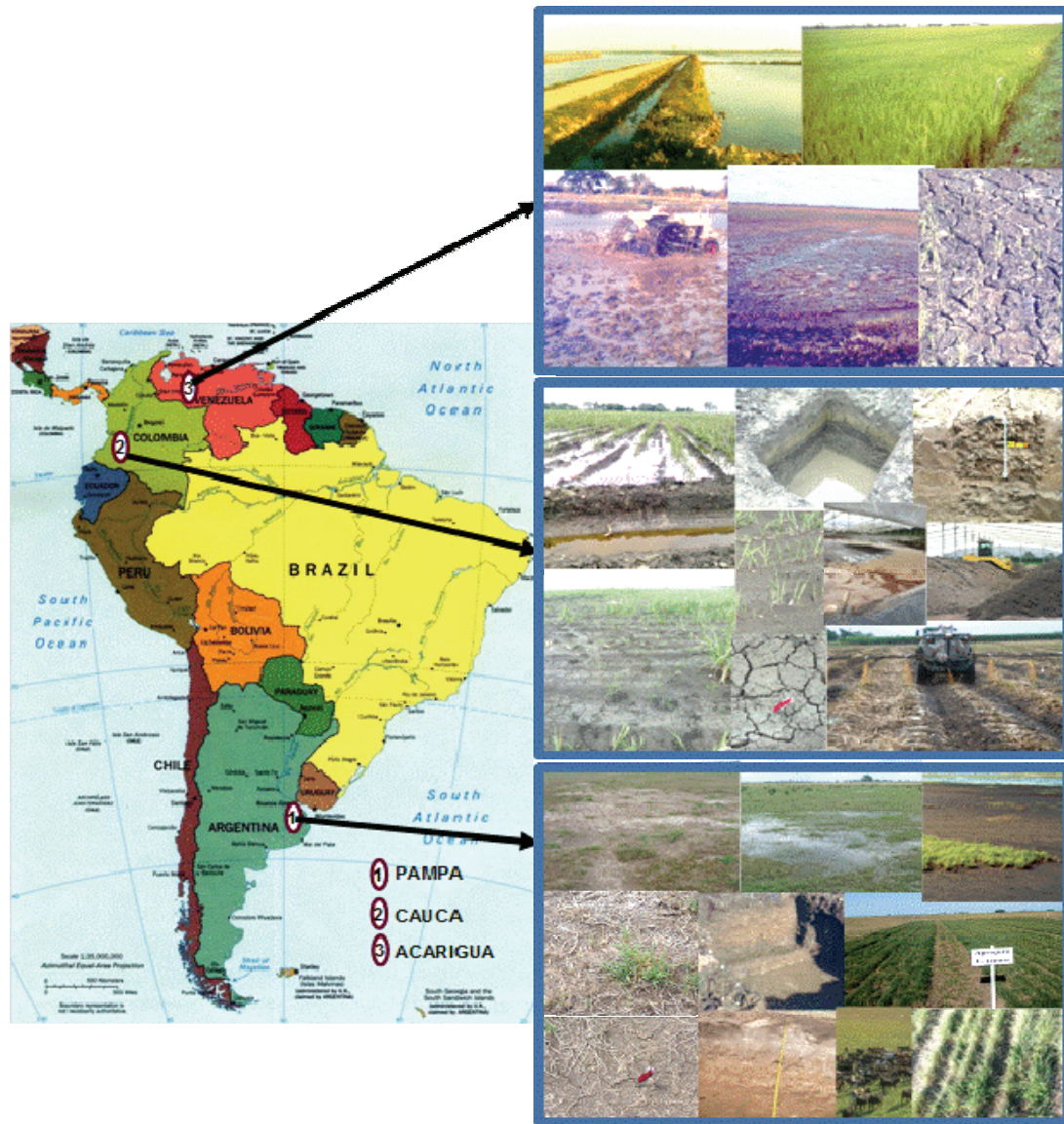

Fig. 7 **Location of the reported case studies, with pictures illustrating the different land use and management systems, the sodicity problems and some of the remedial practices**

The case in the Colombia Cauca Valley (CAUCA), includes problems of water-logging and secondary sodification in irrigated lands with sugarcane, as a result of an inefficient and poor distribution of water by the irrigation system, and of an inadequate drainage management (González, 2001; Madero, 2001; Ramírez, 2012; Ramírez et al., 2014). The problems of sodicity occur even with the use of low salinity and sodicity water for irrigation (Table 3), because due to the application of water in great excess of evapotranspiration, there are maintained relatively low levels of soil salinity, requiring lower SAR for clay dispersion in those soils with predominately illitic clays. The ground-water levels are maintained at 60–120 cm depth, due to the application of an excess of irrigation water, due to the inadequate maintenance and functioning of the drainage system, and due

to seepage from unlined water delivery channels. The sugarcane growth and production is negatively affected by prolonged waterlogging (reduced infiltration, mainly of rainfall) and reduced rooting depth. Besides improving irrigation and drainage systems and management, in the area there was tested the use of an amendment of vinasse alone or composted with foliar residues of the sugarcane to reduce waterlogging. The results up to now are promising, although there are limitations in the amount to be used to avoid potential contamination problems of soils and waters (Sánchez et al., 2014). The vinasse is the main effluent and byproduct of ethanol production from sugarcane (10–15 liters of vinasse per liter of ethanol), acidic, rich in organic matter and with high concentrations of K and a little less of Ca, Mg, S and N.

In the case located in the Western Plains of Venezuela (ACARIGUA) (Pla, 1985), in lands with clay loam to clay soils, continuously cropped with flooded rice (irrigated in the dry season), the sodic soil was sampled after drying the surface soil in between crops (Fig. 8). The land management includes rotary shaking (batido) of the surface soil under saturated conditions to destroy the soil structure, before seeding, and continuous flooding afterwards. The composition of the groundwater and surface soil (Table 3), with very high levels of sodium bicarbonate (and even some carbonates in the dry soil) may be due to reactions, producing Na bicarbonates from Na sulphates under anaerobic conditions (Pla, 1969), as it is shown in Fig. 5. These reactions have been identified and studied in other sodic soils in the same zone (Guerrero et al., 2004, 2007). The problem of sodicity does not effect the rice crop under the present management conditions, but it would not permit afterwards any other crop not allowing continuous flooding. Reclamation of such soils would be very costly and would require a long time, with improved drainage, amendments and grass cover with grasses tolerant to water-logging and salinity.

Table 2   Soils, climate and ground-water levels in the locations of the case studies

Location	Soil	Texture	Clay type	Climate		Ground-water level (cm below surface)
				Dec – Ap R(mm) – ET(mm)	May – Nov R(mm) – ET(mm)	
CAUCA	Entisol (Mollisol)	Clay-loam (Silty-loam)	Ill＞Sme	332 – 502	464 – 718	50 – 120
ACARIGUA	Entisol (Vertisol)	Clay (Clay-loam)	Ver＞Ill＞K	80 – 750	860 – 840	Flooded
PAMPA	Mollisol	Silty-loam	Ill＞Sme	712 – 664 E 221 – 327*	270 – 533 E 177 – 266*	60 – 160(0)+

Dec: December; Ap: April; Nov: November; Ill: Illites; Sme: Smectites; Ver: Vermiculite; K: Kaolinite; R: rainfall; ET: Evapo-transpiration; E: Evaporation; + Occasionally flooded; * Depending on ground-water level.

Table 3   Measured and calculated salinity and sodicity under the different conditions of climate, soils, crop, irrigation system, and irrigation or ground water composition

Location	Crop	Irrigation system	Irrigation water (I) (Ground-water) (G) meq/liter						Resulting soil 0 – 30 cm				
				CA	Na	B	S	Cl	pH	EC$_{SE}$ M	EC$_{SE}$ C	SAR$_{SE}$ M	SAR$_{SE}$ C
CAUCA	Sugar cane	Furrow	(I)	2,8	2,5	3,6	1,4	0,4	7,8	2,5	2,2	21	6
			(G)	3,0	30	11	17	5					
ACARIGUA	Rice	Flooding	(I)	3,5	2,7	4,3	1,2	0,6	9,7	12	13	54	65
			(G)	3,0	16	9,6	4,0	4,6					
PAMPA	Pasture	Dryland	(G)	4,2	8,3	6,0	2,5	4,0	8,7	3,5	3,0	22[*]	26
									9,3	12		54[**]	
									8,2	2,6		12[***]	

* Natural cover (0 – 30 cm); ** Bare soil (0 – 15 cm); *** Planted cover (0 – 15 cm).

CA: Ca+Mg; B: Bicarbonates; S: Sulphates; Cl: Chlorides; EC: Electrical conductivity dSiemens/m; SAR: Sodium Adsorption Ratio; SE: Saturation Extract; M: Measured; C: Calculated.

5   Conclusions

There is shown how the model SALSODIMAR, based on the balance of water and soluble components of

both the irrigation water and groundwater under different water and land management conditions, may be adapted for the diagnosis and prediction of the selected sodicity problems, and for the selection of alternatives for their management and amelioration. The prediction of soil sodicity problems, derived of increased use of low quality irrigation waters, including more or less treated waste-waters, in poorly drained soils, with shallow fluctuating groundwater levels, require adequate simulation modeling. These models have to be based on modeling hydrological processes responsive to water and solute balances in the soil, as influenced by climate, crops and irrigation and drainage management. Soil chemical and physicochemical reactions affecting the relationships of salinity and sodicity levels, have also to be included in modeling. The proposed adaptation of the model SALSODIMAR, that includes all those requirements, gave reasonably good predictions in the preliminary evaluations of sodicity in the different case studies included in this paper. Additional research under field conditions would be needed for further improvement of the model predictions.

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