

SALINITY IS REDUCED BELOW THE EVAPORATION FRONT DURING SOIL SALINIZATION

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RESUMEN. *La salinización de suelos es un problema global. Generalmente, la salinización es causada por el transporte de sales hacia la superficie por capilaridad y, a pesar de su importancia global, los mecanismos que la controlan aún no están bien descritos (Kampf et al., 2005). En este trabajo, se han llevado a cabo experimentos de laboratorio y simulaciones numéricas que muestran que las sales precipitan en el frente de evaporación, el cual se da en una zona estrecha del suelo y que el flujo de vapor de agua se desplaza, no solo en sentido ascendente, sino también descendente, desde dicho frente de evaporación. El flujo de vapor descendente, condensa, causando la dilución de la solución. Esto implica, que contrariamente a lo creído hasta ahora, la salinización (Xu y Shao, 2002) (la precipitación de sales) no se da por debajo del frente de evaporación.*

ABSTRACT. *Soil salinization is a global problem. Salinization is generally caused by salts transported to the soil surface by capillary rising water. Despite its global importance, actual salinization mechanisms are poorly understood (Kampf et al., 2005). We use laboratory experiments and numerical models to show that salt precipitates at the evaporation front, which occurs within a very narrow band. Part of the evaporating water diffuses downwards, where it condensates. This implies that, contrary to widely spread belief, salinization (Xu & Shao, 2002) (i.e. salt precipitation) does not occur below the evaporation front. Instead, the upflowing solution becomes diluted.*

1. INTRODUCTION

The term salinization refers to the precipitation of salts in the soil surface and root zone. These salts are highly soluble, leading to reduced activity of water, which hinders uptake by plants and causes significant losses in agricultural production. This is a global problem. Nearly 50% of irrigated lands in arid and semi-arid regimes (FAO-UNESCO, 1992) (30% of total arable land (Oldeman et al., 1991) suffer some degree of salinization. Salinization is generally viewed as involving two processes (Fujimaki et al., 2006). First, water containing salts is brought to the surface by capillarity. Second, evaporation increases salinity and eventually causes salts to precipitate forming a crust, which may reduce further evaporation. The process is complicated by several factors. The vapor pressure at equilibrium within soil water is given by (Olivella et al. 1996a):

$$e_{veq} = e_{vsat}(T) \cdot a_{ws}(s) \cdot a_{w\psi}(\psi)$$

where $e_{vsat}(T)$ is the vapor pressure at equilibrium with a flat surface of fresh water at a given temperature T , $a_{ws}(s)$ is the activity of water with solute concentration s and $a_{w\psi}$ is an activity correction factor required to account for the fact that soil water is under suction. Increased salinity causes water activity to drop, thus reducing evaporation. Further, activity is equal to the relative humidity of the air at equilibrium with water. Therefore, a reduced activity implies that vapor will tend to flow towards the salinized area (Kelly & Selker,

2001; Wheeting, 1925). Relative humidity, and consequently water activity, a_{wp} , is also affected by suction, which is large in the drying zone. Suction gradients cause an upwards vapor flux from wet to dry soil zones. Finally, energy drives the whole process. During the summer, mean temperature in the soil is lower than at the surface, thus reducing $e_{vsat}(T)$ below the evaporation front. The corresponding reduction in vapor pressure causes a downwards flux of vapor. Such a flux has been observed in desert soils (Scanlon, 1994; Scanlon & Milly 1994). In summary, three competing mechanisms act during soil salinization: an unsaturated flow of liquid, an influence on water activity by salinity and suction and a temperature driven vapor flux. Because of these complexities, soil salinization is generally studied by means of water and salt balances without considering in detail small scale processes (Guganesharajah et al., 2004). This may be sufficient to explain large scale behaviour but probably not for designing effective remediation strategies (Tejedor et al., 2007). While small scale processes have been studied, they have not accounted for salinity (Boulet et al., 1997) or for open systems (Nassar & Horton, 1989a; Nassar & Horton, 1989b; Olivella et al., 1996a). Still, a large number of questions remain unanswered: how deep does salinization penetrate, where the evaporation takes place, is salinization a surface process or can it occur at depth.

2. LABORATORY EXPERIMENT

To answer these questions, we focused on the evaporation phenomenon and performed column evaporation tests. We set up sand and silt columns with varying concentrations of epsomite ($MgSO_4 \cdot 7H_2O$) and halite ($NaCl$). Evaporation was forced by an infrared lamp (*Philips PAR38 IR 175R*) located 38cm above the column surface, so that the radiation at the soil surface was designed to be some $90mW/cm^2$, similar to summer radiation at mid-latitudes. The columns (Figure 1) consisted of methacrylate cylinders, 24cm long and 14.4cm in diameter surrounded by a thermal insulator (*Termoflex*, 2cm thick).

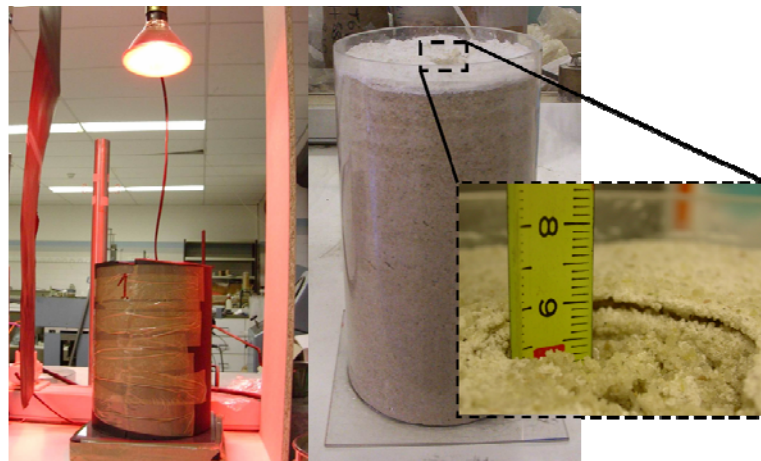


Figure 1: Experimental set up. Left, initial setting under the infrared lamp and the column surrounded by thermal insulator. Right, the column at the end of the experiment, when the sand is dry and a salt crust has formed at the surface. Note the detail of the air gap existing between the sand and the salt crust.

Column weight was monitored and the weight loss was attributed to evaporation. The columns were dismantled when a 32% degree of saturation was reached. Temperature, salt concentration and soil water content profiles were obtained. The column experiments are described in detail in Gran et al. 2009.

Figure 2 displays the time evolution of cumulative evaporation for the different soil and salt types and different concentrations.

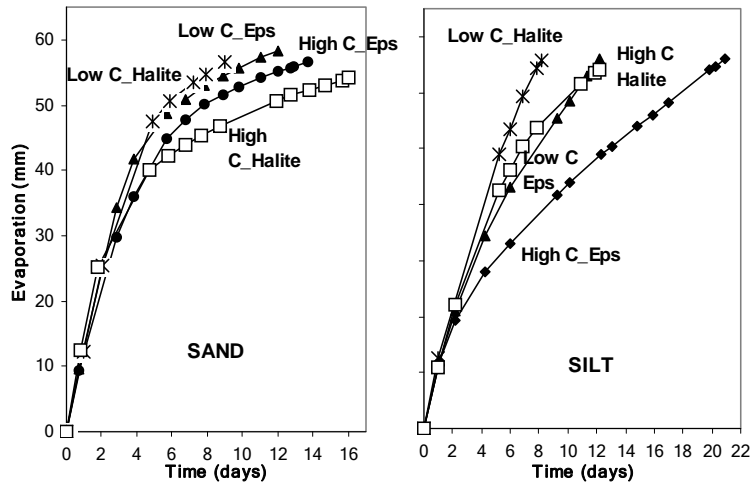


Figure 2: Time evolution of cumulative evaporation for sand and silt columns using halite ($7\text{g}_{\text{NaCl}}/\text{kg}_w$ for the low concentration and $20\text{g}/\text{kg}_w$ for the high concentration column) and epsomite ($14\text{g}_{\text{MgSO}_4 \cdot 7\text{H}_2\text{O}}/\text{kg}_w$ for the low concentration and $40\text{g}/\text{kg}_w$ for the high one).

As the figure illustrates, it is clear that the evaporation rate evolves over time and is sensitive to soil texture and salt. At the beginning, evaporation is fast and controlled by the type of soil. The fact that evaporation occurs more quickly for sand than for silt columns suggests that permeability is a controlling factor. At later times, the situation is reversed, with a higher evaporation rate for silt than for sand columns, which can be attributed to differences in capillary rise.

The upper portion of the sand columns becomes desaturated at late times (Figure 3). That is, evaporation is concentrated within an evaporation front located a few centimetres below the surface. On the other hand, water content remains sizeable all the way up to the surface in silt columns (not shown). The type of salt and concentration also plays a significant role on the evaporation rate, which drops sooner for epsomite than for halite and for saline than for dilute solutions. All these observations are consistent with current understanding (Menking et al., 2005).

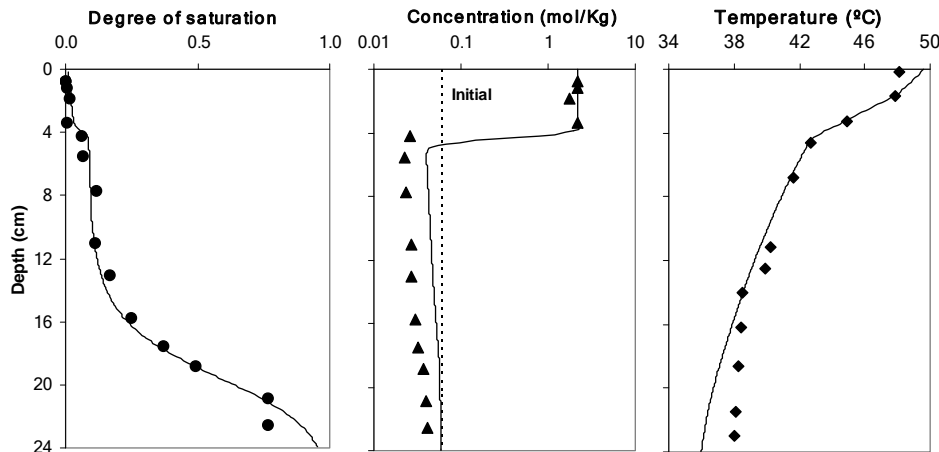


Figure 3: Profiles of concentration, degree of saturation and temperature measured (symbols) and computed (line) after 12 days of evaporation for the sand column with low initial epsomite concentration.

The spatial distribution of solute (Figure 3) is possibly more surprising than the other two profiles. Salinity is extremely high at the surface, where water content is negligible, and salt has precipitated. Unexpectedly, salinity drops dramatically, normally below the initial concentration just underneath the crust. Further down in the sample, salinity remains constant in the case of the silt columns and increases slightly with depth for sand columns.

The decrease of concentration can be explained by the condensation of vapor and suggests that significant separation processes occur during crust formation. The evaporation crust is fed by liquid water, which flows upwards by capillarity towards an evaporation front. Vapor diffuses both upwards and downwards from the front. Downwards vapor flux carries energy and dilutes the lower portions of the column.

3. MODELING

This conceptual model implies a number of interacting processes: liquid and gas flow; solute, vapor and heat transport; osmotic effects; “oven-drying” of the soil (i.e. evaporation of not only capillary water, but also adsorbed water) and salt precipitation.

Identifying the role of each process requires numerical modelling. We used CBR (Saaltink et al., 2004) modified using CHEPRO (Bea et al., 2008) to evaluate salinity using the Pitzer model (Simunek & Suarez, 1994) as well as a modified Van Genuchten (1980) retention and relative permeability curves to simulate oven drying (Fayer & Simmons, 1995; Rossi & Nimmo 1994).

CBR couples the code CodeBright (Olivella, 1996b) and Retraso (Saaltink, 1997). CodeBright simulates the flow of liquid and gas and the transport of heat. It then passes flow properties to Retraso. After Retraso has calculated the concentrations of solutes and minerals, it updates the flow parameters affected by these concentrations, such as, porosity, permeability and water activity.

The model used a one dimensional finite element mesh of 241 nodes with smaller elements at the top of the column. Retention curve parameters were obtained from laboratory measurements and saturated permeability and relative permeability curves were taken from literature. At the top boundary, a constant heat flux was imposed and also a flux of water and air as a function of temperature and relative humidity measured in the laboratory. Along the laterals and at the bottom of the column a heat flux as a function of temperature difference between column and laboratory was used, whereas zero fluxes for air and water were imposed. Finally, zero mass fluxes for the solutes were imposed on all boundaries.

Because the important processes (formation and evolution of an evaporation front and a salt crust) were most pronounced for the sand column with epsomite, this case has been used for the numerical simulations.

Results of the non isothermal multiphase flow model are shown in Figure 4 and Figure 5 for the sand column with a low initial epsomite concentration. (A comparison of model results and laboratory measurements was shown in Figure 3).

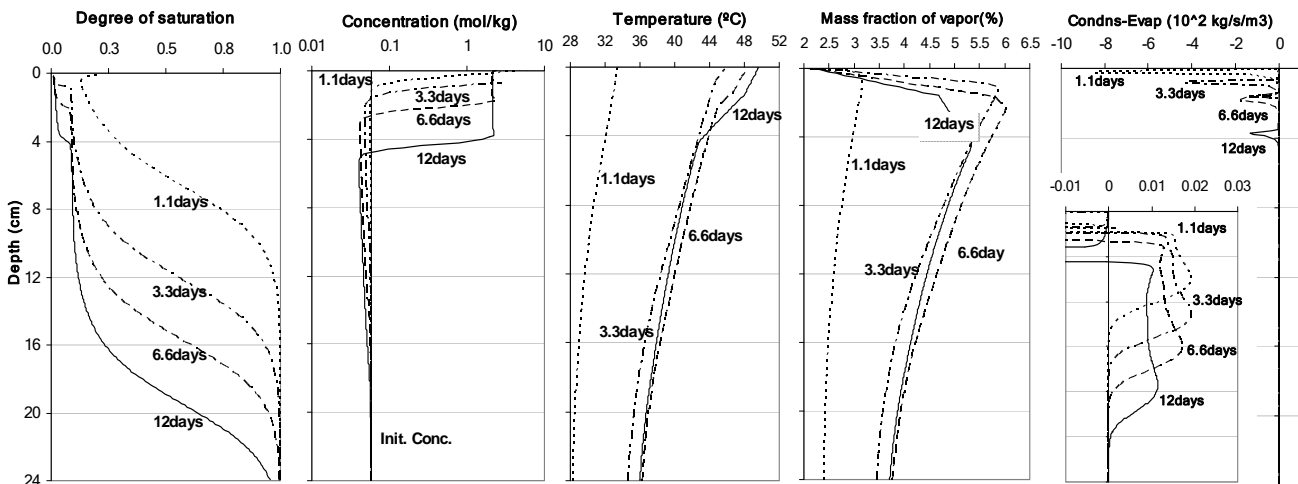


Figure 4: Computed profiles of degree of saturation, concentration, temperature, vapor mass fraction and condensation (evaporation when negative). Notice the change in temperature and vapor mass fraction slope at around 2cm depth after 12 days due to the crust simulated reduction in vapor diffusivity and increase in thermal conductivity. Notice that significant evaporation only occurs on a very narrow band.

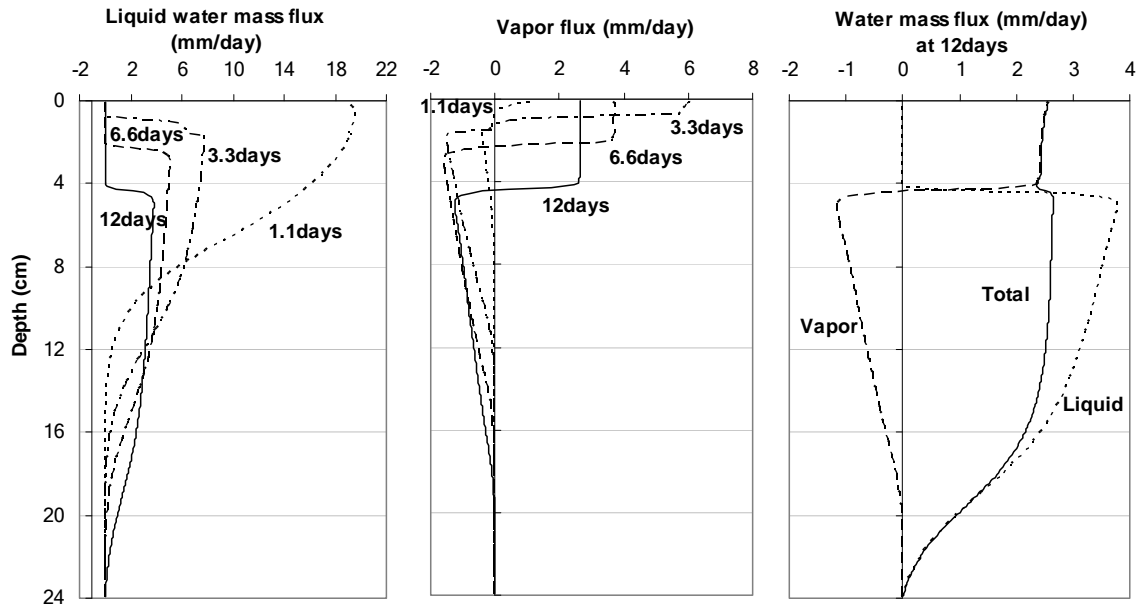


Figure 5: Computed water mass fluxes (positive if upwards) expressed as water column (1mm/d = 1kg/m²/d). Liquid water flux is always upwards, but negligible above the evaporation front. Vapor flux is upwards above the evaporation front and downwards below. Total water flux is approximately constant in the upper part of the column (the slight reduction at the evaporation front accounts for storage variations in the oven drying zone).

The model qualitatively reproduces the observed moisture, temperature and salinity patterns (Figure 3) and allows a detailed evaluation of the processes controlling these variables. Liquid water flows upwards towards the evaporation front where moisture drops abruptly to oven dry conditions. This implies that water can no longer flow as liquid. However, water content continues to diminish towards the top of the column in response to the upwards increase in temperature and a reduction of vapor pressure which causes relative humidity to drop in upward direction. In reality, though not simulated here, the reduction in relative humidity causes dehydration of epsomite, such that MgSO₄ minerals are progressively dehydrated.

The behaviour of the temperature profiles is more predictable. Most incoming heat is initially dissipated by evaporation at the early stages. Therefore, the top of the column heats up once evaporation starts to fall. As a result, an increasing proportion of energy is returned as sensible heat. Temperature gradients are largest above the evaporation front because most energy is needed for evaporation. A portion of the downwards energy flux underneath the evaporation front takes place not as sensible heat, but as latent heat flow.

Salt concentration is the critical factor. The liquid becomes saturated with epsomite at the centre of the front. Therefore the location of the front is controlled by the heat flux from above (reduced because of depth and dryness) and the liquid water flux from below (also reduced as water content falls over time). As concentration increases and the soil dries, water activity is reduced and the front is displaced downwards.

As a result, evaporation is forced to occur at the precipitating salts front. The increase in vapor and gas pressure at the evaporation front causes vapor diffusion and advection both upwards and downwards from this front. The relative magnitude of the two fluxes depends on boundary conditions. In the experiments discussed here, upwards diffusion was hindered by the salt crust, which forced large downwards diffusion, the consequent condensation and a measurable dilution. Vapor also diffuses downwards prior to crust formation for the sand and silt columns, but its magnitude is much smaller. In all cases, the downward vapor flux is more than compensated by liquid flow in the upwards direction, because the overall water content reduces in the column at all stages of the process.

4. CONCLUSIONS

Several conclusions can be drawn. From a mechanistic point of view, evaporation divides the soil into two markedly different zones. Above the evaporation front, the soil is dry, contains salts and the water flux is restricted to vapor phase. Below the evaporation front, the soil is relatively wet (above irreducible water content), water flows upwards in liquid form, and downwards in vapor form. This downward vapor flow condensates causing salinity to drop below the evaporation front. The mechanism displays positive feedbacks, as condensation will be most intense in areas of highest salinity, thus diluting saline water that may have infiltrated. Implications for salt management are clear. Evaporation occurs solely at the surface only if water is abundant (either because of flooding or fine soil texture) and will tend to produce salinization unless saline water is drained away. Alternatively, salinization may be controlled by reducing evaporation (e.g. by soil mulching) or by forcing it to occur far from the root zone (e.g. by drip irrigation).

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