WATER AND SALT DYNAMICS AND THE HYDRAULIC CONDUCTIVITY FEEDBACK: IRREVERSIBLE SOIL DEGRADATION AND RECLAMATION OPPORTUNITIES

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Question

Soil salinization is a major cause of land degradation in agricultural lands, especially in arid and semi-arid regions. At least **20% or irrigated lands in the world are salt-affected**, with serious implications to food security in the face of changing climate patterns and increasing global population. The dynamics of salt accumulation is not well understood, in particular the role of nonlinear feedbacks and stochastic inputs in creating **irreversible degraded states** and in soil rehabilitation efforts.

Here we investigate the role of an important feedback on the system dynamics: the decrease in saturated hydraulic conductivity as the soil becomes more sodic or less saline.

Salinity and sodicity

Soil salinity: high concentrations of salt in the soil. Decreases soil water potential, reduces agricultural yields.

Soil sodicity: sodium constitutes a large portion of overall cations, not necessarily accompanied by high salinity levels. Negative effects on soil structure, reduced hydraulic conductivity, waterlogging, increased risk of erosion.

The dynamics of salinity and sodicity in the root zone is mediated by the transport of water in the soil, which depends on water inputs (rainfall, irrigation), the soil physical and chemical properties, environmental conditions, among other factors.

$$\text{water} \quad \frac{ds}{dt} = \text{infiltration} - \text{percolation} - \text{evapotranspiration}$$

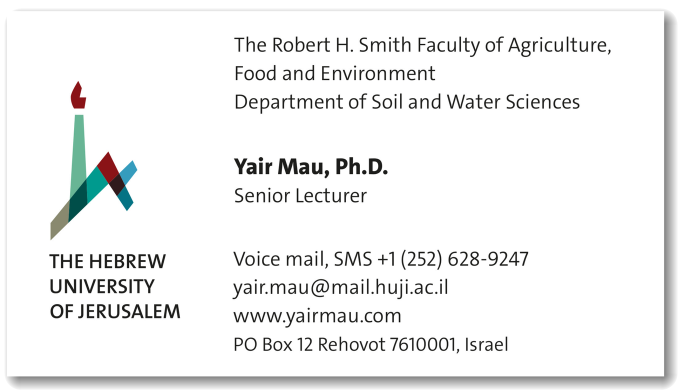
$$\text{salinity} \quad \frac{dC}{dt} = \frac{IC_I}{nZ_r s} - \frac{I-T}{nZ_r s}C = \text{irrigation} - \text{leaching}$$

$$\text{sodicity} \quad \frac{dE}{dt} = \text{cumbersome nonlinear function of } (s, C, E)$$

We assume a vertically averaged root zone, where sodium and calcium cations in the soil solution and exchange complex are in local equilibrium (Gapon Equation). This system of equations is amenable to analysis, which can reveal steady-state and dynamical properties.

Mau and Porporato [2015]

Contact



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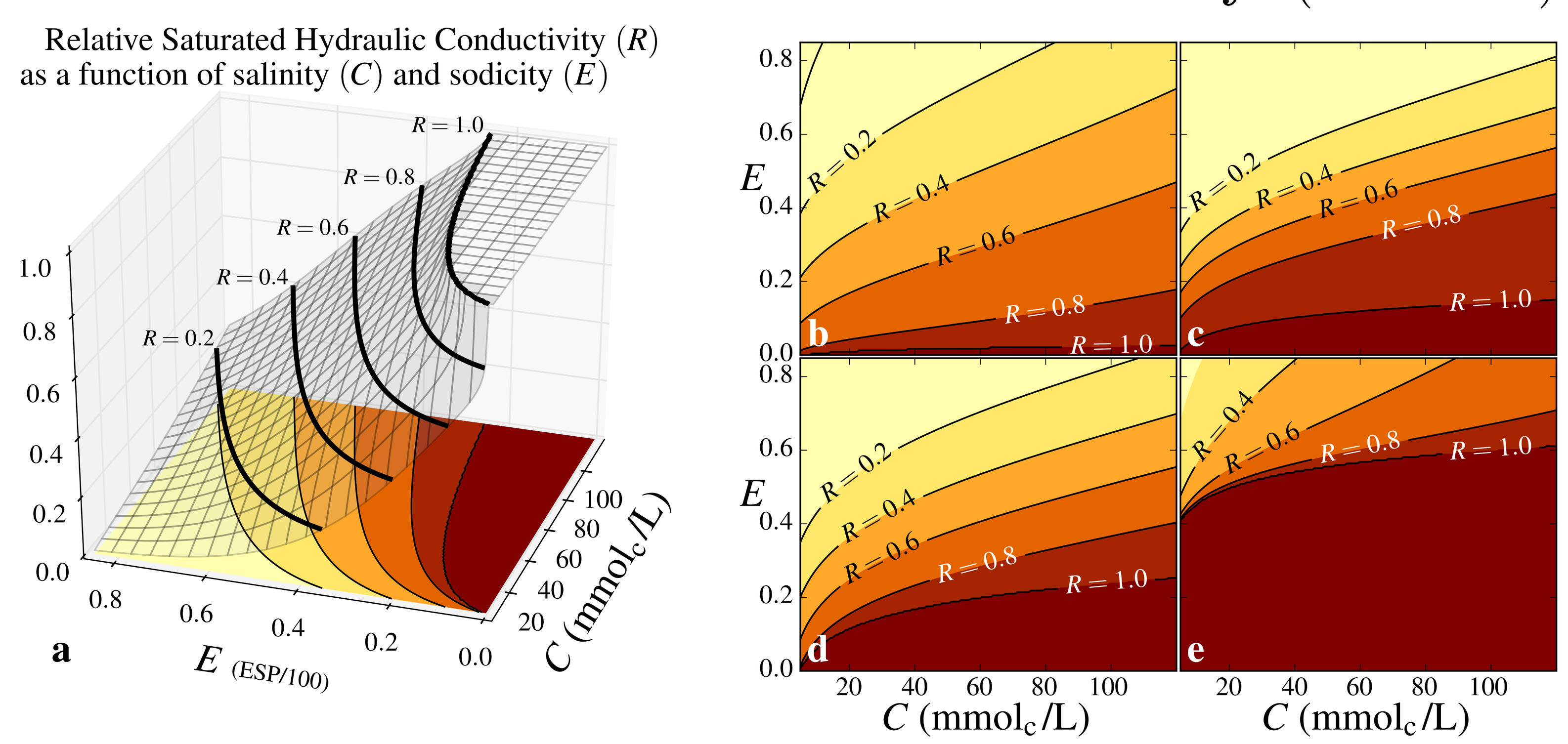
Hydraulic conductivity feedback

High sodicity and low salinity cause clay swelling and dispersion, thus decreasing the Relative Saturated Hydraulic Conductivity (R). Clayey soils are more sensitive to this kind of soil structure degradation.

sensitivity: (b>c>d>e).

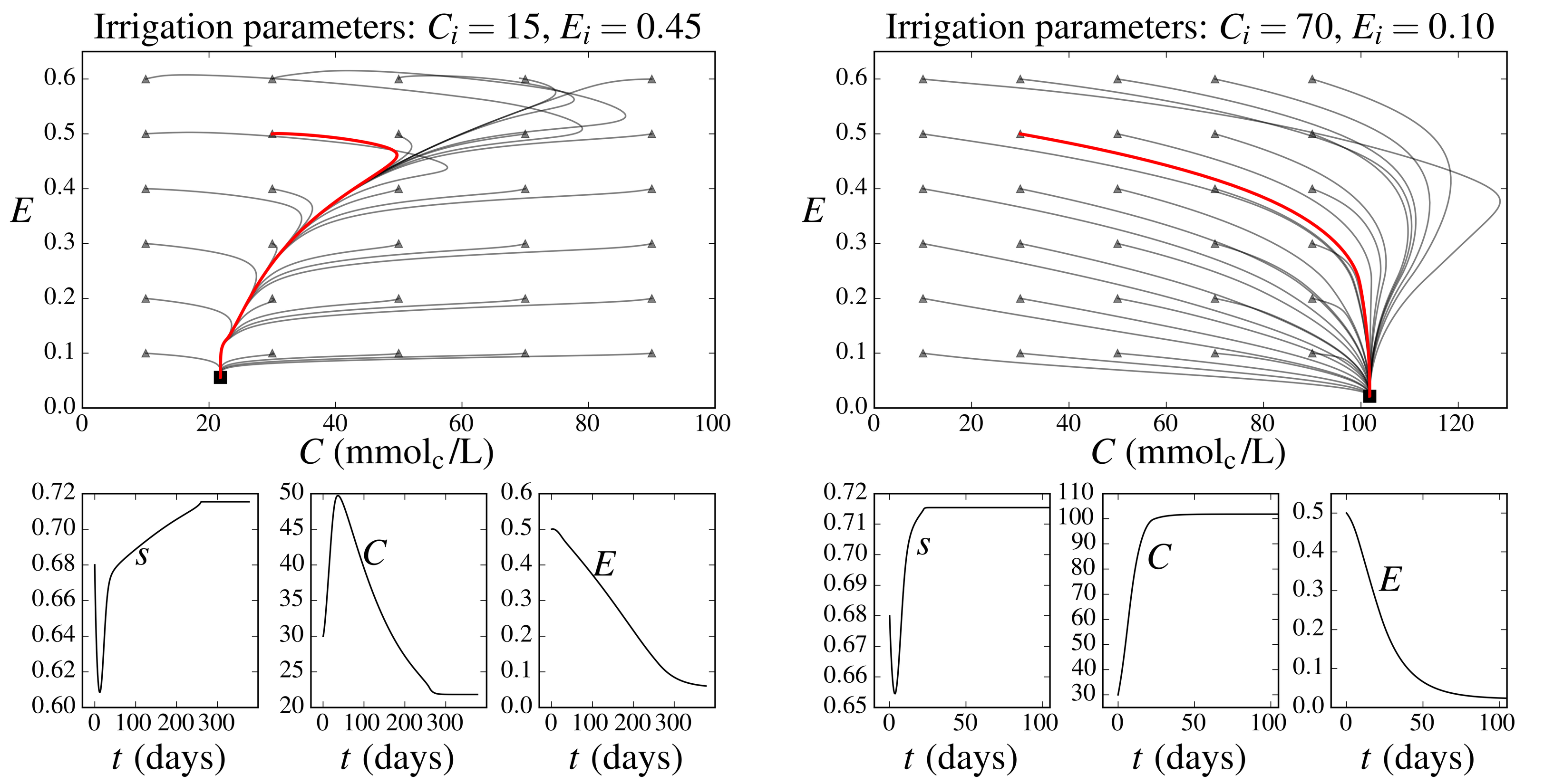


Ezlit et al. [2013], McNeal [1968]

The feedback mechanism: high sodicity causes reduction in hydraulic conductivity, which in turn further hinders sodium leaching.

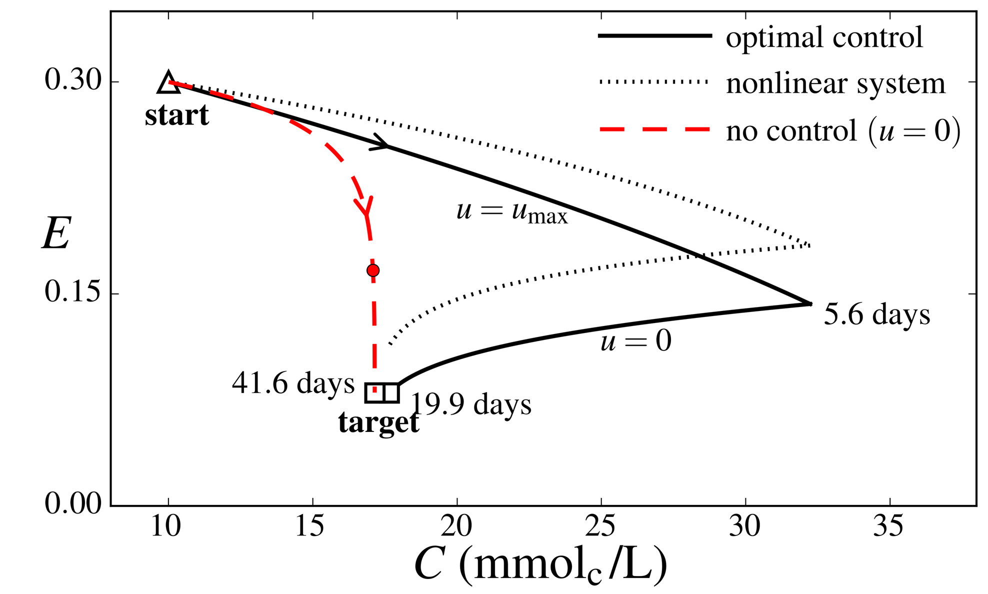
Time scales

Flow in phase-space (s, C, E) and time scales depend on the control parameters (for the figures below, irrigation water salinity and sodicity C_i, E_i).



Soil water s has the shortest time scale, its evolution is determined ("enslaved") by the variables C and E. For good quality irrigation water (left), evolution is much slower than for saline irrigation water (right), because the trajectory passes closer to the intersection of the nullclines $ds/dt = 0$, $dC/dt = 0$. The lower the electrolyte concentration of the input water, the longer the time scale of sodicity evolution, effectively characterizing irreversibility.

Reclamation of degraded states



Mau and Porporato [2016], Porporato et al. [2015]

Because of fast s dynamics, the system can be simplified to only two equations, yielding deeper insights. For example, understanding the time scale dynamics can help us devise optimal reclamation strategies. Here we see a "bang-bang" control, where fertigation with calcium cations is discontinuously switched off in order to achieve **time-optimal** reclamation. This modeling approach can be combined with detailed numerical simulations and experiments in order to fine-tune the suggested optimal strategies.

Further steps

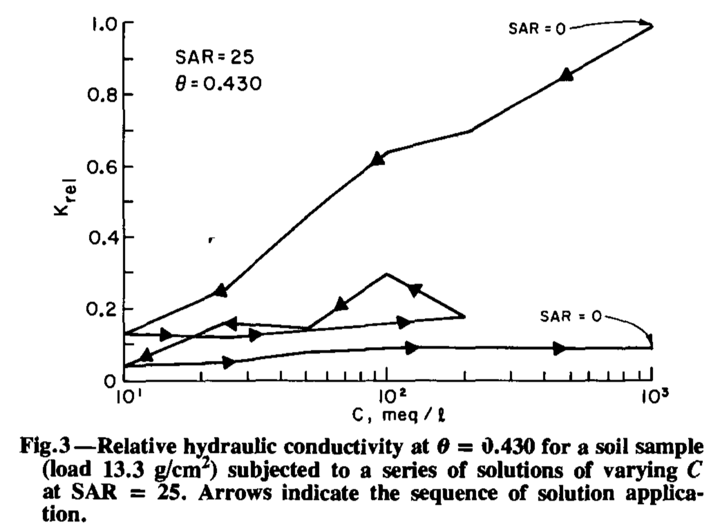


Fig. 3—Relative hydraulic conductivity at θ = 0.430 for a soil sample (load 13.3 g/cm²) subjected to a series of solutions of varying C at SAR = 25. Arrows indicate the sequence of solution application.

Dane and Klute [1977]

The Relative Saturated Hydraulic Conductivity (R) clearly depends on the history of the system. Once clay has been dispersed, it is not enough to increase the concentration of input water C_i and expect hydraulic conductivity to return to its previous values (true irreversibility). A modification of the function for R, that incorporates a hysteresis mechanism, will yield more realistic dynamics, and will change drastically the dynamics. This includes bistability of degraded and non-degraded states for the same environmental conditions and critical thresholds for irreversible soil degradation.

References

Yair Mau and Amilcare Porporato. A dynamical system approach to soil salinity and sodicity. *Advances in Water Resources*, 83:68–76, 2015

Yair Mau and Amilcare Porporato. Optimal control solutions to sodic soil reclamation. *Advances in Water Resources*, 91:37–45, 2016

Amilcare Porporato, Xue Feng, Stefano Manzoni, Yair Mau, Anthony J. Parolari, and Giulia Vico. Ecohydrological modeling in agroecosystems: Examples and challenges. *Water Resources Research*, 51(7):5081–5099, 2015. doi: 10.1002/2015wr017289

YD Ezlit, J McL Bennett, SR Raine, and RJ Smith. Modification of the mcneal clay swelling model improves prediction of saturated hydraulic conductivity as a function of applied water quality. *Soil Science Society of America Journal*, 77(6):2149–2156, 2013

BL McNeal. Prediction of the effect of mixed-salt solutions on soil hydraulic conductivity. *Soil Science Society of America Journal*, 32(2):190–193, 1968

J.H. Dane and Arnold Klute. Salt effects on the hydraulic properties of a swelling soil. *Soil Science Society of America Journal*, 41(6):1043–1049, 1977