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Stochastic Modeling of Soil Salinity

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Large areas of cultivated land worldwide are affected by soil salinity. Estimates report that 10% of arable land in over 100 countries, and nine million km2 are salt affected, especially in arid and semi-arid regions. High salinity causes both ion specific and osmotic stress effects, with important consequences for plant production and quality. Salt accumulation in the root zone may be due to natural factors (primary salinization) or due to irrigation (secondary salinization).

Simple (e.g., vertically averaged over the soil depth) coupled soil moisture and salt balance equations have been used in the past. Despite their approximations, these models have the advantage of parsimony, thus allowing a direct analysis of the interplay of the main processes. They also provide the ideal starting point to include external, random hydro-climatic fluctuations in the analysis of long-term salinization trends.

We propose a minimalist stochastic model of primary soil salinity, in which the rate of soil salinization is determined by the balance between dry and wet salt deposition and the intermittent leaching events caused by rainfall events. The long term probability density functions of salt mass and concentration are found by reducing the coupled soil moisture and salt mass balance equation to a stochastic differential equation driven by multiplicative Poisson noise. The novel analytical solutions provide insight on the interplay of the main soil, plant and climate parameters responsible for long-term soil salinization. In fact, soil salinity statistics are obtained as a function of climate, soil and vegetation parameters. These, in turn, can be combined with soil moisture statistics to obtain a full characterization of soil salt concentrations and the ensuing risk of primary salinization. In particular, the solutions show the existence of two quite distinct regimes, the first one where the mean salt mass remains nearly constant with increasing rainfall frequency, and the second one where mean salt content increases markedly with increasing rainfall frequency. As a result, relatively small reductions of rainfall in drier climates may entail dramatic shifts in long-term soil salinization trends, with significant consequences e.g. for climate change impacts on rain-fed agriculture.

The analytical nature of the solution allows direct estimation of the impact of changes in the climatic drivers on soil salinity and makes it suitable for computations of salinity risk at the global scale as a function of simple parameters. Moreover it facilitates their coupling with other models of long-term soil-plant biogeochemistry.