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Modeling pedogenesis at multimillennium timescales: achievements and challenges

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The modeling of soil genesis is a particular case of modeling vadose zone processes, because of the variety in processes to be considered and its large (multimillennium) temporal extent. The particular relevancy of pedogenetic modeling for non-pedologists is that it involves the soil compartment carbon cycle. As most of these processes are driven by water flow, modeling hydrological processes is an inevitable component of (non-empirical) modeling of soil genesis. One particular challenge is that both slow and fast pedogenetic processes need to be accounted for.
This overview summarizes the state of the art in this new branch of pedology, achievements made so far and current challenges, and is largely based on one particular pedon-scale soil evolution model, SoilGen.
SoilGen is essentially a pedon-scale solute transport model that simulates unsaturated water flow, chemical equilibriums of various species with calcite, gypsum and gibbsite as precipitated phases, an exchange phase of Na, K, Ca, Mg, H and Al on clay and organic matter and a solution phase comprising various cations and anions. Additionally, a number of pedogenetic processes are simulated: C-cycling, chemical weathering of primary minerals, physical weathering of soil particles, bioturbation and clay migration. The model was applied onto a climosequence, a chronosequence, a toposequence and as part of a spatio-temporal soilscape reconstruction. Furthermore, the clay migration component has been calibrated and tested and so has the organic matter decomposition component. Quantitative comparisons between simulations and measurements resulted in the identification of possible improvements in the model and associated inputs, identified problems to be solved and identified the current application domain.
Major challenges for process-based modeling in the vadose zone at multimillennium timescales can be divided into 4 groups: (i) Reconstruction of initial and boundary conditions; (ii) Accounting for evolution in soil properties such as soil texture and soil structure; (iii) Developing adequate calibration techniques; (iv) Maximizing computational efficiency.
Reconstruction of initial and boundary conditions requires multidisciplinary inputs either derived from proxies or from combined vegetation and climate development models. So far, the combination of pedogenetic models and combined vegetation/climate models is rare.
At pedogenetic timescales, soil characteristics that are usually considered constant become dynamic: texture, OC, bulk density, precipitated salts, minerals, etc. Interactions and feedbacks between these characteristics and associated hydrological properties need attention, e.g. via pedotransfer functions. The same can be stated for the development of soil structure and associated preferential flow, which is still a challenge.
At multimillennium temporal extents, the combination of long model runtime and the fact that most calibration data represent the current stage of soil development requires a special approach. Model performance can be evaluated at various timescales using unconventional proxies.
Finally, recognizing the fact that matter redistribution at the landscape scale is of paramount importance at multimillennium extent requires the formulation of computationally efficient 3D models. This will surely involve analysis of the tradeoff between process detail, model accuracy, required boundary inputs and model runtime.