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Modeling critical zone processes in intensively managed environments

Praveen Kumar, Phong Le, Dong Woo, and Qina Yan
University of Illinois, Civil and Environmental Engineering, Urbana, Illinois, United States (kumar1@illinois.edu)

Processes in the Critical Zone (CZ), which sustain terrestrial life, are tightly coupled across hydrological, physical, biochemical, and many other domains over both short and long timescales. In addition, vegetation acclimation resulting from elevated atmospheric CO_2 concentration, along with response to increased temperature and altered rainfall pattern, is expected to result in emergent behaviors in ecologic and hydrologic functions, subsequently controlling CZ processes. We hypothesize that the interplay between micro-topographic variability and these emergent behaviors will shape complex responses of a range of ecosystem dynamics within the CZ. Here, we develop a modeling framework ('Dhara') that explicitly incorporates micro-topographic variability based on lidar topographic data with coupling of multi-layer modeling of the soil-vegetation continuum and 3-D surface-subsurface transport processes to study ecological and biogeochemical dynamics. We further couple a C-N model with a physically based hydro-geomorphologic model to quantify (i) how topographic variability controls the spatial distribution of soil moisture, temperature, and biogeochemical processes, and (ii) how farming activities modify the interaction between soil erosion and soil organic carbon (SOC) dynamics. To address the intensive computational demand from high-resolution modeling at lidar data scale, we use a hybrid CPU-GPU parallel computing architecture run over large supercomputing systems for simulations. Our findings indicate that rising CO_2 concentration and air temperature have opposing effects on soil moisture, surface water and ponding in topographic depressions. Further, the relatively higher soil moisture and lower soil temperature contribute to decreased soil microbial activities in the low-lying areas due to anaerobic conditions and reduced temperatures. The decreased microbial relevant processes cause the reduction of nitrification rates, resulting in relatively lower nitrate concentration. Results from geomorphologic model also suggest that soil erosion and deposition plays a dominant role in SOC both above- and below-ground. In addition, tillage can change the amplitude and frequency of C-N oscillation. This work sheds light in developing practical means for reducing soil erosion and carbon loss when the landscape is affected by human activities.