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From grid-average to hillslopes: Adding subgrid topography and lateral water redistribution to the LPJ-GUESS terrestrial ecosystem model

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Large-scale ecosystem models often exhibit substantial uncertainty when simulating topographically complex landscapes because fine-scale microclimate and hydrologic connectivity are poorly represented within coarse grid cells. This uncertainty can propagate into limitations in capturing climate responses in water, carbon, and nitrogen cycling, especially during seasonal transitions and high- and low-flow periods. Here, we extended the widely used dynamic ecosystem model LPJ-GUESS by linking sub-grid topographic heterogeneity to ecosystem functioning through (i) topography-conditioned microclimate and (ii) lateral hillslope water redistribution, while maintaining consistency in coupled nitrogen losses.

Within a standard 0.5° grid cell, we discretize the landscape into representative topographic types based on elevation and aspect. Temperature and incoming shortwave radiation are adjusted per type using elevation, slope, and aspect, allowing vegetation and soil processes to respond to locally resolved climate conditions per topographical type. Hydrology is extended with slope-dependent partitioning between infiltration and runoff, and a daily lateral transfer scheme that redistributes surface and subsurface water downslope through simple storage/retention, thereby introducing the time-lagged hydrologic response absent from the default vertical-only bucket structure. We find that enhanced downslope drainage can unrealistically intensify nitrogen leaching at low landscape positions, so we further implement a nitrogen constraint that limits leaching under weak percolation and represents stronger retention at wetter, low-elevation areas.

We evaluate stepwise model versions in the Krycklan catchment (northern Sweden) using multi-variable observations, including catchment outlet discharge and eddy-covariance measured ecosystem evapotranspiration and carbon fluxes. Introducing sub-grid heterogeneity into LPJ-GUESS reduces runoff seasonality biases and improves performance against observed water and carbon fluxes relative to the default LPJ-GUESS. Our model development within LPJ-GUESS offers a transferable scheme to improve sub-grid topographical process representation in heterogeneous

landscapes, and contributes to better simulations of ecosystem responses to climate variability and extremes.