EXTREME-SCALE MODELING—UNDERSTANDING ECOHYDROLOGIC DYNAMICS UNDER CLIMATE CHANGE

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EXECUTIVE SUMMARY

The elevation of atmospheric CO_2 increases the ratio of carbon fixation to water loss of plants or water-use efficiency. This shift in ecosystem functioning is central to understanding the cycles of water, energy and carbon under climate change. However, the magnitude of the effects on ecohydrologic dynamics, such as soil moisture content, surface runoff, and ponding dynamics controlled by microtopographic variability on the land surface, remains unclear. The goal of this project is to develop efficient and robust predictive models on a hybrid central processing unit-graphics processing unit (CPU-GPU) architecture for capturing the mechanism of vegetation acclimation and its link to hydrologic processes. This utilization of Blue Waters marks the **first** investigation on the impacts of vegetation acclimation under climate change on ecohydrologic dynamics at light detection and ranging (LIDAR)-resolution over large scales.

INTRODUCTION

Amongst the most important potential environmental changes is the elevation of atmospheric carbon dioxide concentrations\(CO_2), predicted to increase to 550 ppm by 2050 and probably exceed 700 ppm by the end of the 21st century [1]. One of the primary concerns with rising CO_2 under climate change is its potential to alter the hydrologic cycle through vegetation acclimation and modifications in evapotranspiration. Several models are being used to investigate the heterogeneity and process complexity of the soil-vegetation-atmosphere interactions in ecosystems under global warming. The common approach among these models is the coupling of a land surface model (LSM) with a distributed, either physically-based or simplified, hydrological model to capture the feedback cycles between the biosphere and atmosphere. However, these models have not incorporated capabilities to capture processes dominated by micro-topographic features on the land surface.

This work directly targets the development of a predictive capability for investigating micro-topographic controls on ecohydrologic dynamics under climate change over large scales in a massively parallel architecture that allows us to explicitly incorporate emerging high-resolution LIDAR measurements.

METHODS & RESULTS

We coupled a multi-layer canopy model [2,3] (MLCan) with a conjunctive surface-subsurface flow model [4] (GCSFlow) to capture the acclimatory responses of vegetation to global warming, then predict how these changes affect ecohydrologic dynamics on landscapes at LIDAR-scale resolution. While MLCan is a biophysical model that simulates the eco-physiological acclimations of vegetation under climate change, GCS-flow is an integrated surface–sub-surface flow model utilizing LIDAR-resolution topographic data to capture the micro-topographic controls on hydrologic processes. The MLCan-Flow3D model is implemented on a hybrid CPU-GPU parallel computing environment to overcome challenges associated with the high density of computational grid and nonlinear solvers. Specifically, MLCan is implemented at all nodes covered by vegetation using Message Passing Interface (MPI), and GCS-flow is implemented using the CUDA platform.

We performed simulations using LIDAR topographic data in the Goose Creek watershed of the Upper Sangamon River Basin (USRB) in central Illinois. This watershed is intensively managed for agriculture and is part of the Critical Zone Observatory for Intensively Managed Landscapes (IML- CZO). Maize and soybean are two major crops planted in rotation every year in the study area. The model runs are performed with three different scenarios contrasted to evaluate the impacts of vegetation acclimation on ecohydrologic dynamics under climate change.

Changes in ecohydrological dynamics dominated by micro-topographic features in response to elevated CO_2 and air temperature increase are presented in Figure 1. We showed that rising CO_2 is likely to decrease evapotranspiration, thus increase soil moisture and surface water and ponding dynamics. However, as higher temperature is also considered, there is a net increase in evapotranspiration, leading to a reduction in soil moisture storage and ponding persistence. Thus far, using Blue Waters we have demonstrated that hybrid computing is feasible for detailed, extreme-scale ecohydrologic modeling, which has been previously assumed to be an intractable computational problem.

WHY BLUE WATERS

Blue Waters has been critical for this project. To our knowledge, all existing ecohydrologic models have not incorporated capabilities to simultaneously capture vegetation acclimation under climate change and processes dominated by micro-topographic features. The unique computational power of Blue Waters associated with MPI-CUDA-aware capability is allowing us to conduct detailed ecohydrologic simulations at **emerging** LIDAR resolution over large domains for the **first** time and to rigorously study the impacts of micro-topographic variability on ecohydrologic dynamics.

NEXT GENERATION WORK

We aim to develop additional components based on the current model that provides powerful tools to conduct simulations and explore various scientific questions in ecohydrology and biogeochemistry.

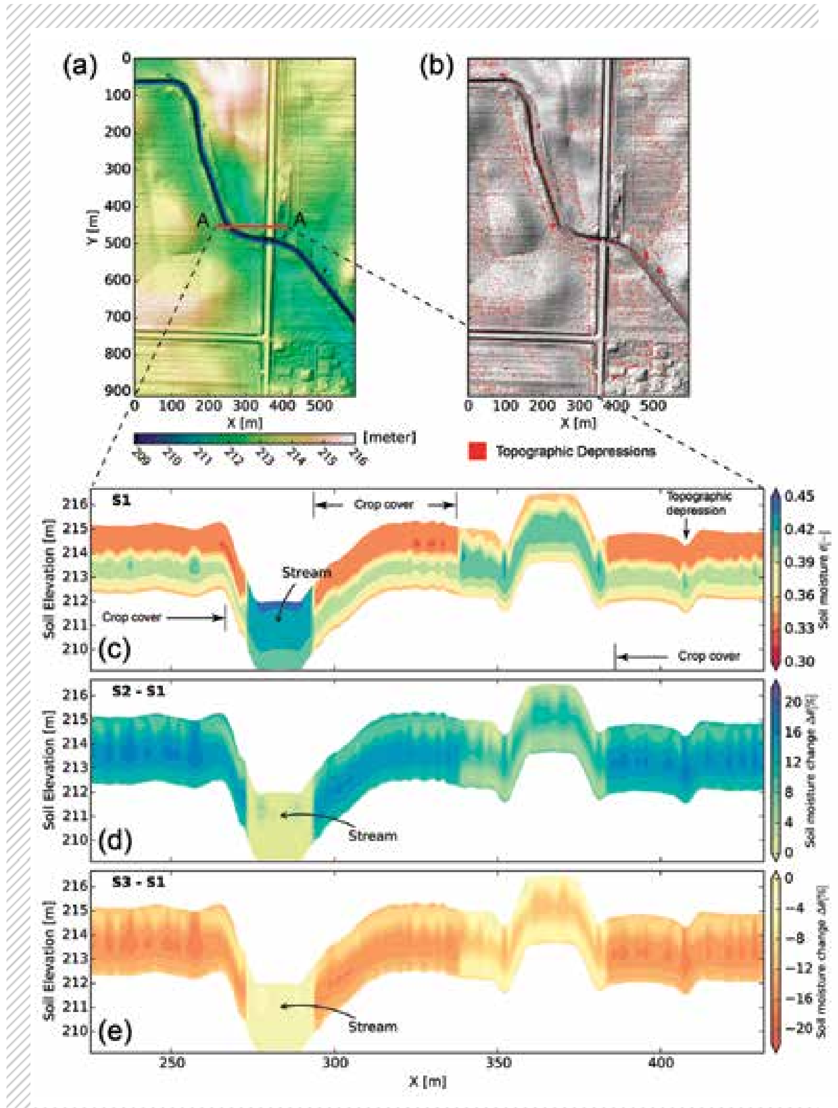

FIGURE 1: Comparison of soil moisture profile under present (S1) and elevated (S2, S3) CO_2 conditions. (a) LIDAR data of a zoomed area within the simulation domain. (b) Map of topographic depressions identified using LIDAR data in Goose Creek watershed. (c) Snapshot of soil moisture profile over depth in cross-section A-A at DOY 230 in 2005 growing season. (d) Difference of soil moisture profile over depth between S1 and S2 scenarios. (e) Difference of soil moisture profile over depth between S1 and S3 scenarios.