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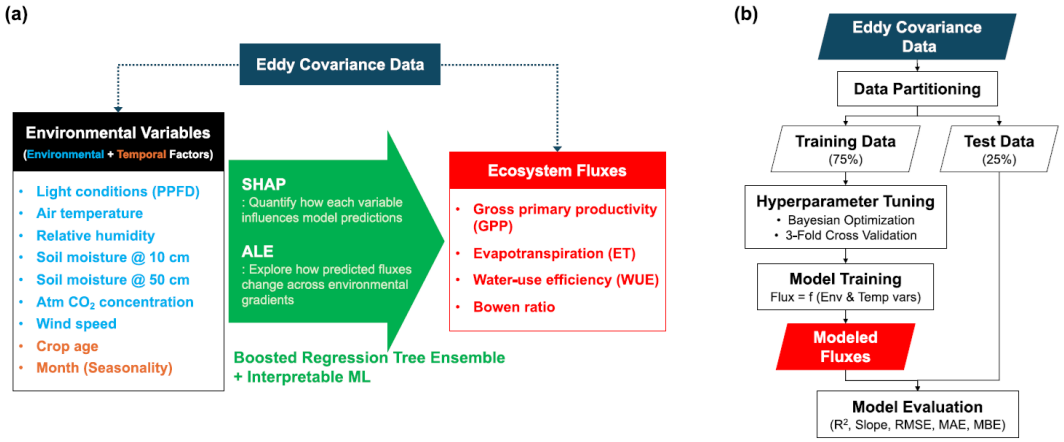
Contrasting Carbon-Water-Energy Dynamics in Perennial and Annual Bioenergy Agroecosystems Using Eddy Covariance and Interpretable Machine Learning

Background/Objective

Understanding how functional differences between perennial and annual bioenergy crops govern carbon (C), water, and energy fluxes is critical for optimizing bioeconomy productivity and resilience. Most previous studies examining the sensitivity of crop C and water fluxes to environmental drivers have relied on short-term measurements that cannot resolve nonlinear interactions or long-term variability, leaving the complex and interdependent effects of multiple environmental drivers poorly understood. To address this gap, this work integrates long-term eddy covariance observations with interpretable machine learning.

Approach

Researchers analyzed 55 site-years of high-frequency eddy covariance observations from five agroecosystems – two perennial grasses (miscanthus and switchgrass), two annual rotation systems (maize-soy and sorghum-soy), and a restored native prairie to examine ecosystem-scale C, water, and energy fluxes. They used an interpretable ML framework with regression tree ensembles, Shapley Additive Explanations, and Accumulated Local Effects to quantify how environmental and temporal factors regulate gross primary productivity (GPP), evapotranspiration (ET), water use efficiency, and the Bowen ratio.



Overview of the analytical framework (a) and machine learning workflow (b) used in this study.

Results

Perennials showed stronger physiological buffering and maintained fluxes across a broader range of temperature and moisture conditions. Annuals, in contrast, showed greater short-term variability and stronger coupling to atmospheric demand, with rapidly declining GPP and ET under low humidity or soil moisture. Together, these results demonstrate that crop life cycle and canopy structure are fundamental determinants of ecosystem-scale C-water-energy coupling.

Significance/Impacts

This work highlights how conversion from annual to perennial feedstocks can enhance resilience and alter land-atmosphere feedbacks. These findings provide a data-driven basis for improving crop and Earth-system models and for guiding bioenergy landscape design under a variety of climate scenarios.

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