Overview of EPA-WED's Eco-Hydrologic Modeling Framework for Assessing Ecosystem Service Trade-offs in Response to Changes in Climate and Land Use

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Models have long played an important role in ecological risk assessments conducted by the U.S. Environmental Protection Agency. Reflecting EPA's prevailing risk assessment paradigm since the early 1980s (NRC 1983; USEPA 1992), models typically have been used to assess single or narrow sets of endpoints. For example, risk assessments concerning water quality or air quality traditionally have been treated as isolated issues by distinct program offices within EPA. The EPA recently established the Ecosystem Services Research Program (ESRP) to help formulate methods and models that consider broader sets of endpoints (http://www.epa.gov/ecology/). Under this new paradigm, the ESRP aims to develop comprehensive risk assessments that quantify how multiple ecosystem services interact and respond in concert to environmental changes. A major goal is to assess how alternative climate and land use scenarios will simultaneously affect tradeoffs in food and fiber production, water quality and quantity regulation, greenhouse gas regulation, and other services. *Essential to this goal are highly integrated models that can be used to define policy and management strategies for entire ecosystems, not simply individual components of the ecosystem.* In this context, an ideal model is one that (1) can unambiguously link effects to causes by identifying key processes that control ecosystem service tradeoffs, (2) can be applied to a wide variety of ecosystems and regions, (3) can be implemented using readily available data, (4) can efficiently map "bundles" of ecosystem services across wide spatial and temporal scales – plots to regions, days to decades, and (5) can provide a user-friendly decision support framework for assessing outcomes of alternative policies and management decisions.

The EPA Western Ecology Division (EPA-WED) has collaborated with the Georgia Institute of Technology and the Marine Biological Laboratory to develop an eco-hydrology modeling framework that meets these emerging risk assessment objectives more closely than other currently available models. This framework links a suite of spatially-distributed, process-based models to address the effects of changes in climate, land use and other interacting stressors on multiple ecosystem services: production of food and fiber, carbon sequestration, regulation of water quality and quantity, reduction of greenhouse gases (CO_2, N_2O, NO_x), and regulation of sources and sinks of reactive nitrogen (Nr) within watersheds. Initial applications of this framework are being conducted for the Ecosystem Services Research Program's ~30,000 km^2 Willamette River Basin Study in western Oregon (http://www.epa.gov/ecology/pdfs/esrp-factsheet-willamette.pdf), and for a collaborative research effort with EPA Region 7 to assess the effects of rangeland burning on air quality and other ecosystem services for the ~25,000 km^2 Flint Hills Ecoregion of Kansas (http://epa.adamskibbe.com/Assets/Info/R7%20RARE%20Summary_rbm_24Oct08.pdf). A major product of this research will be maps that quantify spatial and temporal changes in key ecosystem services throughout the Willamette Basin and Flint Hills region in response to changes in land use and climate.

A central model in this framework is GTHM-MEL, a spatially-distributed eco-hydrology model that links a land surface hydrology model (GTHM, the Georgia Tech Hydrologic Model) with a terrestrial biogeochemistry model (MEL, the Multiple Element Limitation model). The coupled GTHM-MEL differs from other available ecohydrology models in its simplicity, flexibility, and theoretical foundation. For the hydrologic component, the GTHM model is typically applied using 30 x 30-meter landscape units, although user-defined units of any size and shape are possible (m^2 to km^2). GTHM requires calibration of just three parameters to simulate evapotranspiration, infiltration, and surface and subsurface runoff (Pan et al. 2007). In contrast, HSPF, the primary hydrologic model in EPA's BASINS water quality assessment framework, requires calibration of dozens of parameters (http://www.epa.gov/waterscience/basins/basinsv3.htm). For the biogeochemical component, MEL uses a novel resource-optimization algorithm based on economic theory (Bloom et al. 1985; Chapin et al. 1987) that efficiently simulates how plants and microbes allocate their internal assets (biomass, proteins, carbohydrates…) to acquire multiple resources from the environment (H_2O, NH_4, NO_3, DON, PO_4, CO_2, light). For example, as the availabilities of different resources change in response to land use or climate, vegetation in MEL acclimates by reallocating biomass and other internal assets to maintain a balanced uptake for all resources. This approach ensures that all resources in the environment equally limit the productivity of plants or microbes, thereby preventing too many assets from being expended for acquiring non-limiting resources. No other biogeochemical model shares this capability. MEL details and references can be found at http://ecosystems.mbl.edu/research/models/mel/welcome.html.

Thus, the coupled GTHM-MEL provides a more realistic approach for simulating the integrated responses of vegetation, soil and water resources to interacting stressors. The model is well-suited to predicting changes in carbon sequestration in plants and soils, pollution of surface waters, and the severity of floods and droughts affecting regional water supplies – all vital ecosystem services that pose major policy and regulatory issues for EPA and other federal and state agencies. Current work also includes an assessment of riparian buffer effectiveness for reducing nitrogen export to streams in agricultural watersheds, with an emphasis on identifying best management practices acceptable to crop growers and water quality regulators (McKane et al. 2007). Because GTHM-MEL is broadly applicable to any ecosystem – grasslands, agricultural systems, forests, arctic tundra, etc. – it provides a consistent framework for analyzing and comparing stressor effects across regions. The model is implemented for a given location using readily available data for climate (daily precipitation and minimum and maximum temperature), and GIS layers for vegetation type, soil chemical and physical properties and land use (e.g., see Flint Hills data "Atlas" at http://epa.adamskibbe.com/). The model runs on a daily time step and explicitly simulates the cycling and transport of water and nutrients (NH_4, NO_3, DON, DOC and PO_4) for interconnected landscape units, and subsequent discharge to surface waters. Terrestrial biogeochemical processes include gross photosynthesis, autotrophic and heterotrophic respiration, nutrient uptake by plants and microbes, vegetation growth and biomass allocation, detritus production and decomposition, formation of soil organic matter, transformations of inorganic and organic P, N fixation, N mineralization, nitrification, denitrification, and production of dissolved organic nitrogen (DON) and carbon (DOC).

GTHM-MEL is a computationally intensive model and is most appropriate for assessments that require an in-depth understanding of ecosystem service responses at small (first-order) to medium (fourth- and fifth-order) watershed scales. For assessments at much larger scales (e.g., the Willamette Basin or the Flint Hills) GTHM will be linked with PSM (Plant Soil Model), a much simpler and more computationally efficient biogeochemistry model (Stieglitz et al. 2006). PSM uses just four differential equations to simulate daily changes in total plant and soil C and N stocks, DON, DOC and dissolved inorganic nitrogen (DIN). This simplicity dramatically increases the speed and scale of GTHM-PSM applications, albeit while sacrificing GTHM-MEL's process-level detail. To address this drawback we are using fine-scale output from GTHM-MEL to develop simple regression-based algorithms for GTHM-PSM, which can then more efficiently extrapolate eco-hydrologic responses across large spatial and temporal scales.

Ongoing work is aimed at validation tests of GTHM-MEL and GTHM-PSM for several Long Term Ecological Research (LTER) sites: the HJ Andrews Experimental Forest in Oregon's Willamette Basin; the Konza Prairie in the Flint Hills of Kansas; and the Hubbard Brook Watershed in New Hampshire. Initial results show good agreement for key ecosystem processes, including stream discharge and chemistry, vegetation productivity and soil C and N dynamics.

Finally, we will collaborate with Oregon State University to link GTHM-PSM with ENVISION, a decision support tool that integrates landscape GIS layers, ecological models, economic valuation models, and user-defined stressor scenarios (http://envision.bioe.orst.edu/). The linkage of GTHM-PSM and ENVISION will provide EPA clients and other stakeholders with a user-friendly, visual interface for exploring the consequences of alternative climate and land use scenarios on ecosystem service tradeoffs. Outputs will be computer-generated visualizations of predicted changes in multiple ecosystem services, both in biophysical and economic terms. Target ecosystem services will include production of food and fiber, carbon sequestration, regulation of water quality and quantity, reduction of greenhouse gases (CO_2, N_2O, NO_x), and regulation of sources and sinks of reactive nitrogen (Nr) within watersheds. To summarize, our main goal is to provide a framework for integrated assessments that identify policy and management strategies for entire ecosystems and the bundled services they provide, rather than piecemeal assessments of individual services.

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