Advancing coupled water-energy-carbon processes within SWAT toward improved watershed sustainability assessment

Xuesong Zhang and Collaborators (listed on relevant slides)

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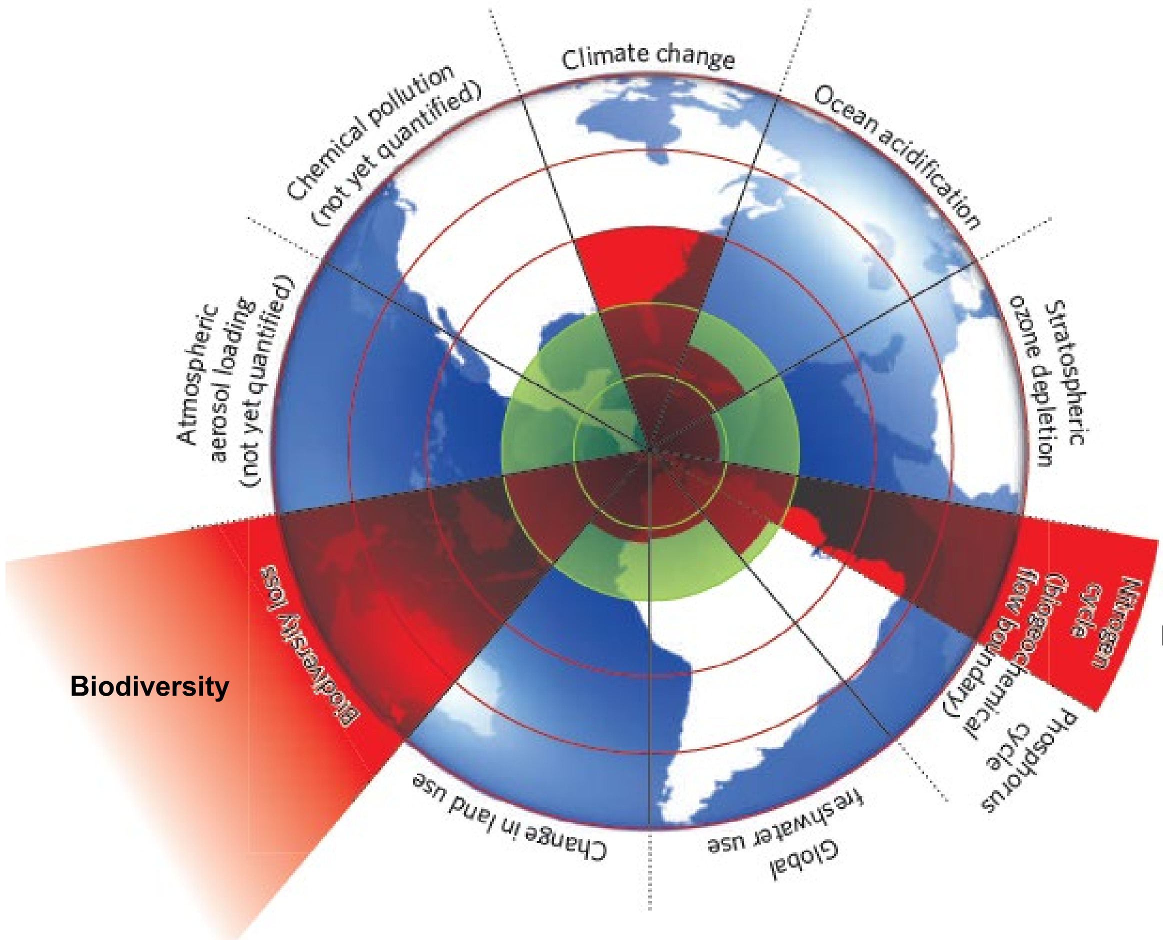
Outline

- General background
- D1: Soil water and wetland module development and testing
- D2: Soil temperature module for characterizing freeze-thaw cycle (Moved to backup slides)
- D3: Coupled terrestrial-aquatic carbon cycling at the watershed scale

Global Sustainability Challenges



Johan RockstrOm (2009, Nature)

D1: Physically-based soil water routing

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SWAT built-in vs. Richards equation

- SWAT built-in method $$Q_{p,i} = (SW_i - FC_i)\left[1 - exp\left(\frac{-24K_{sat,i}}{SAT_i - FC_i}\right)\right]$$

where FC_i is the soil water content at field capacity (mm), $K_{sat,i}$ is the saturated hydraulic conductivity (mm h^{-1}), SAT_i is the amount of water when completely saturated (mm) for *ith* layer.

- Richards equation

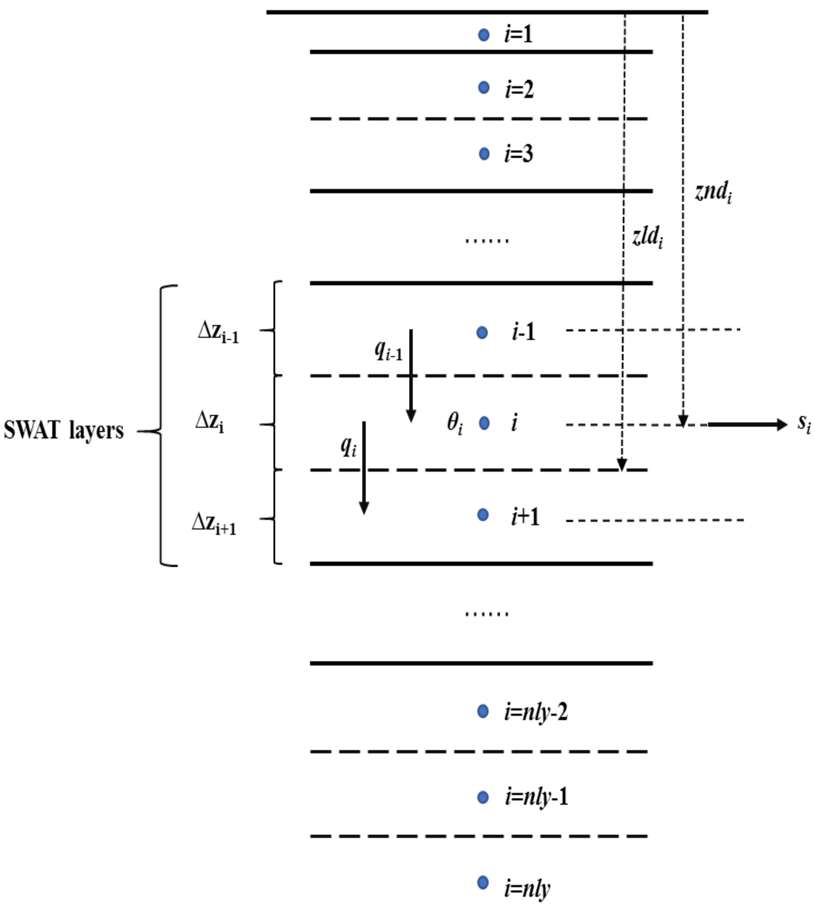
Richards, 1931 $$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[k\left(\frac{\partial h}{\partial z} + 1\right)\right] - Q$$

Zeng and Decker, 2009 $$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[k\left(\frac{\partial(h - h_e)}{\partial z}\right)\right] - Q$$

where θ is the volumetric soil water content (mm^3 mm^{-3}), t is time (s), z is the depth below soil surface (mm; positive downwards), k is the hydraulic conductivity (mm s^{-1}), h is the soil matric potential (mm), h_e is the equilibrium soil matric potential (mm), and Q is a soil water sink term (mm mm^{-1} s^{-1}).

Qi, J., Zhang, X., McCarty, G.W., Sadeghi, A.M., Cosh, M.H., Zeng, X., Gao, F., Daughtry, C.S., Huang, C., Lang, M.W. and Arnold, J.G., 2018. Assessing the performance of a physically-based soil moisture module integrated within the Soil and Water Assessment Tool. *Environmental Modelling & Software*.

Richards equation based soil water routing

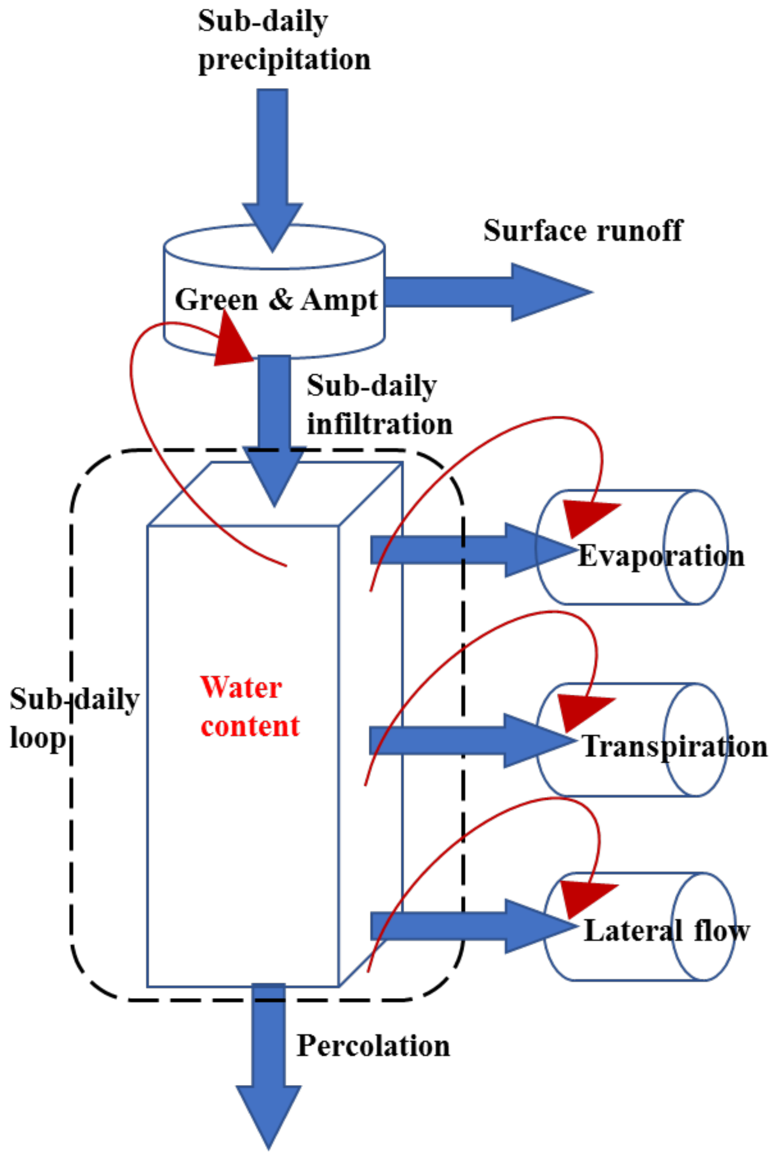


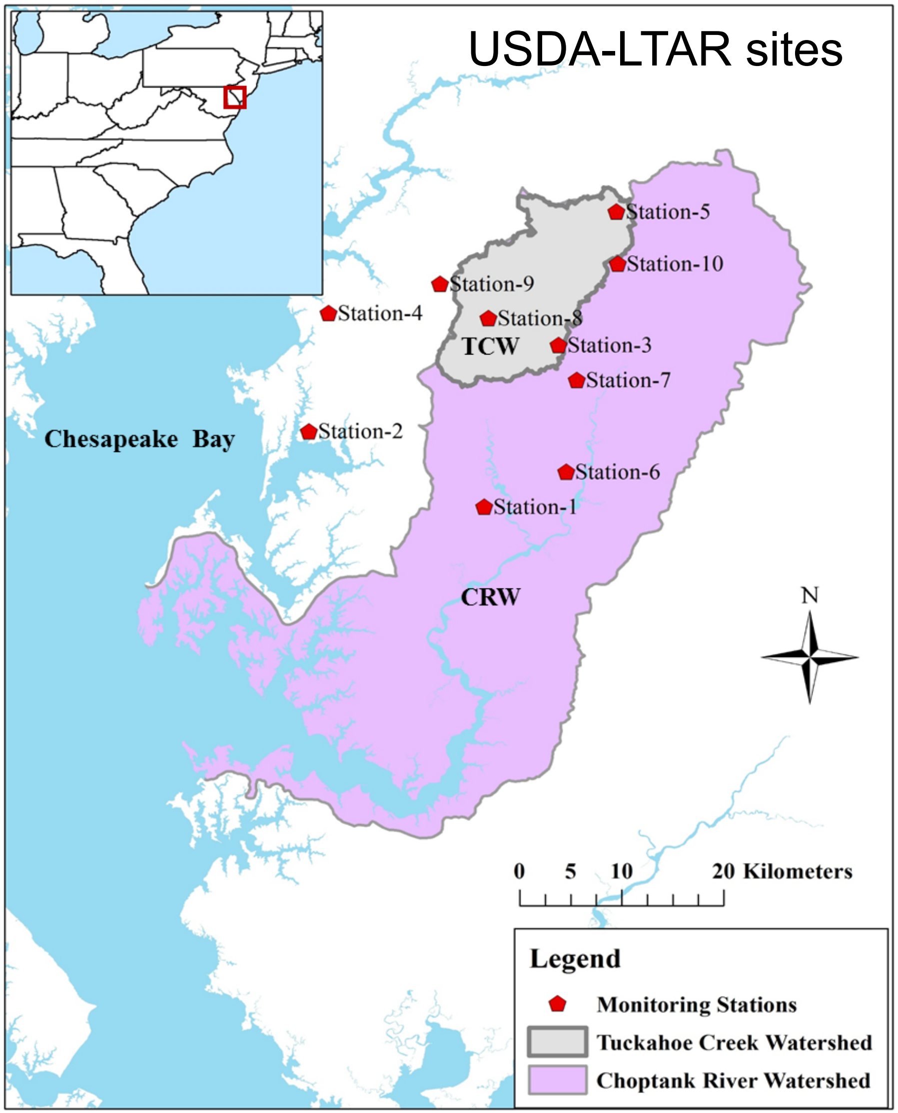
Finite difference with time using the fully implicit scheme resulting in a discretized equation as,

$$\Delta z_i \frac{\theta_i^{n+1} - \theta_i^n}{\Delta t} = q_{i-1}^{n+1} - q_i^{n+1} - s_i$$

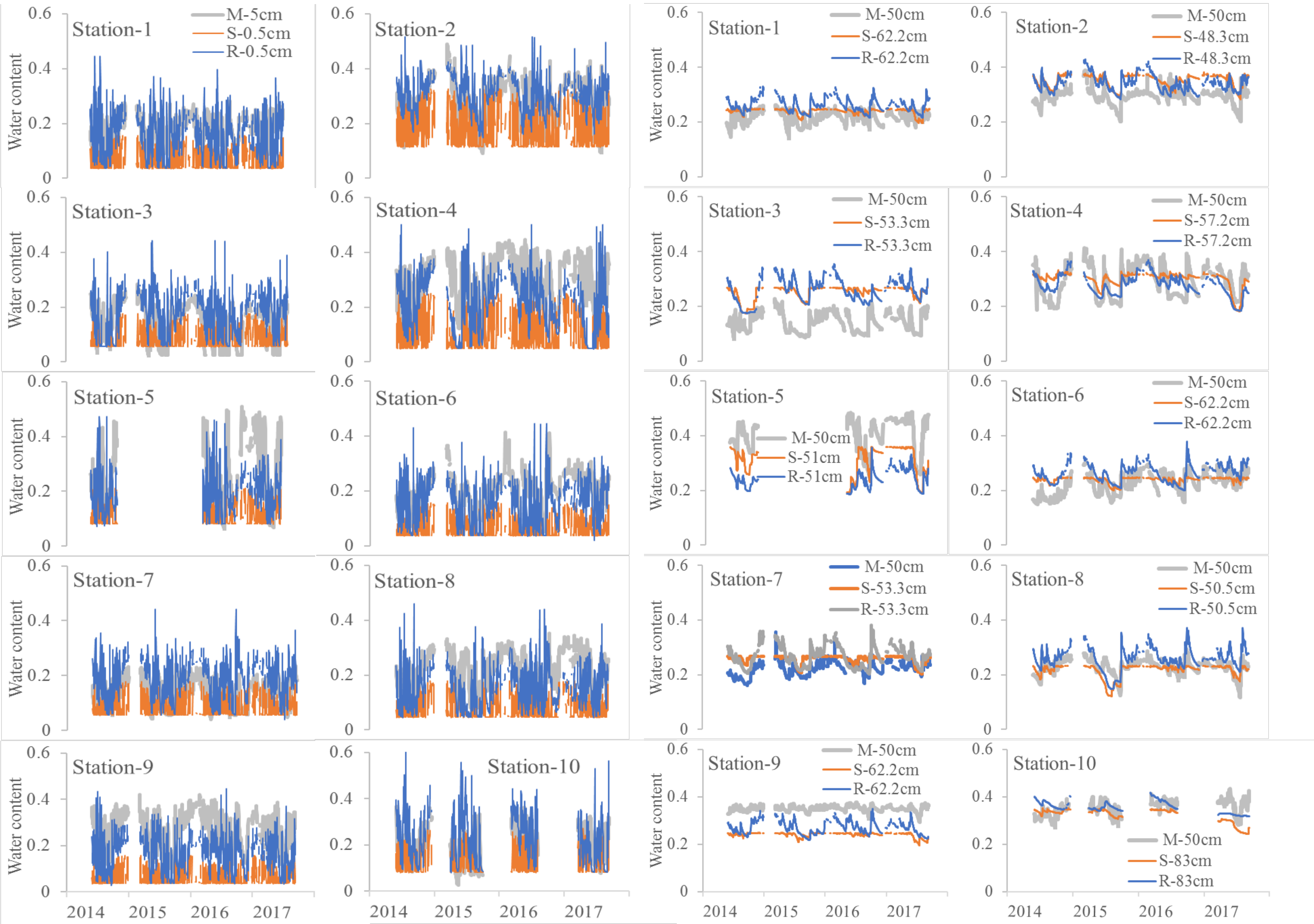
where Δz_i is the thickness (mm) of soil layer *i*, Δt is the time step (s), θ_i^{n+1} and θ_i^n are water content of soil layer *i* for n+1 and n time step, q_i^{n+1} is the water flux across the interface zld_i, q_{i-1}^{n+1} is the water flux across interface zld_{i-1}, and s_i is a layer averaged water sink term defined positive for flow out of the layers (mm s^{-1}) for time step n+1.

Conceptual framework of soil water module



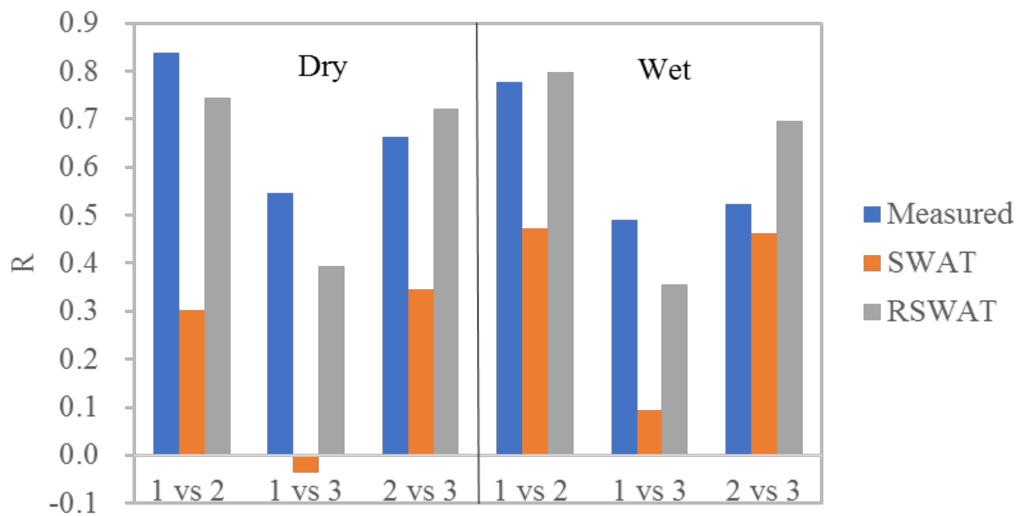


Simulated vs observed soil water content



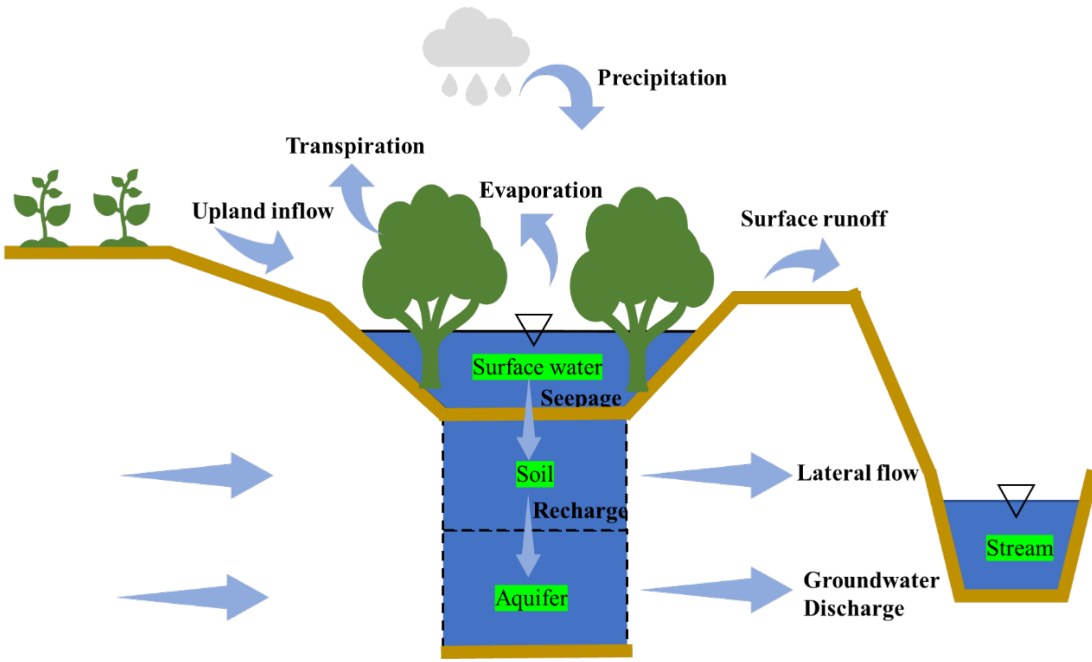
Soil water coupling strength between layers

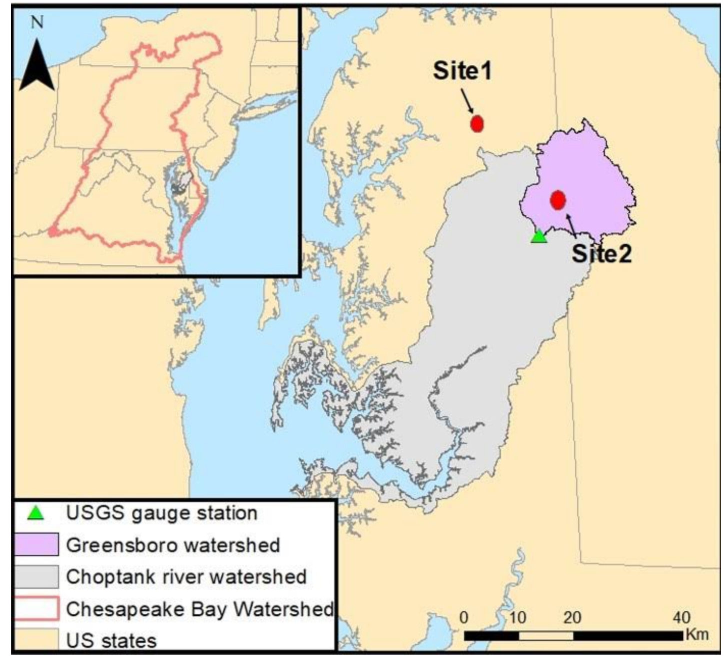
- Improved coupling strength between soil water in different layers is critical for effective assimilation of remote sensing observations of surface soil moisture

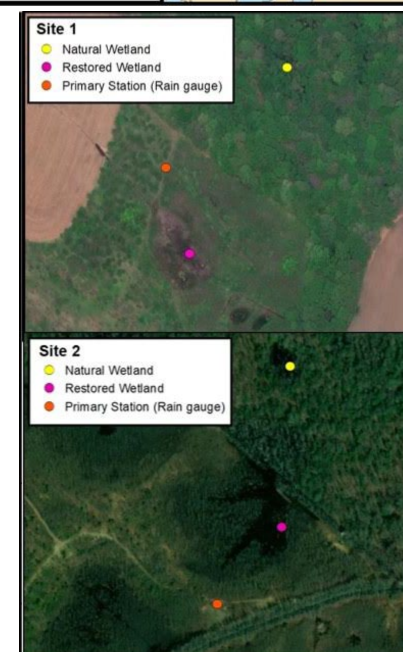


Average soil moisture coupling strength between three soil layers during dry and wet periods, respectively, for the 10 stations. Numbers 1, 2, and 3 denote soil moisture at soil depths of 5, 10, and 50 cm, respectively.

Physically-based wetland water dynamics module



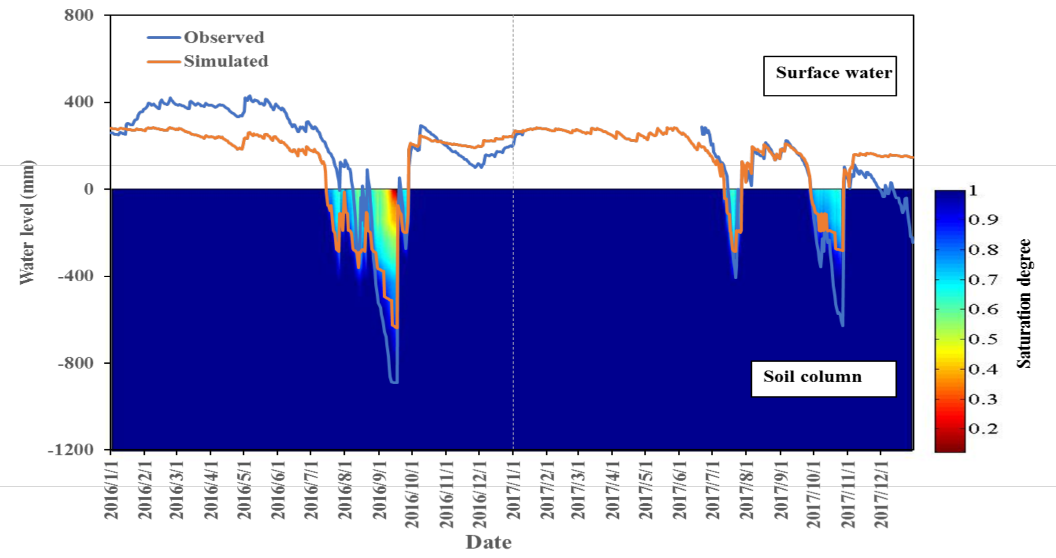




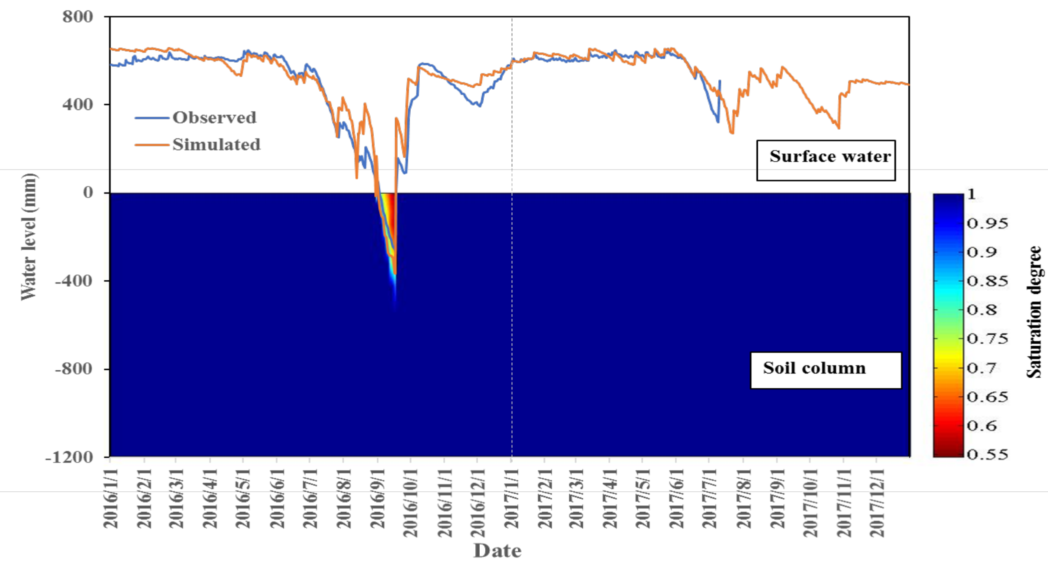
- Hydrological cycle and water balance for a conceptualized wetland in a watershed
- Field data of water level measured in natural and restored forest wetlands as part of USDA LTAR and CEAP

Wetland module evaluation for wetlands without impermeable layer

Observed *vs.* simulated daily water level for the restored wetland at Site #2 from 2016 to 2017.

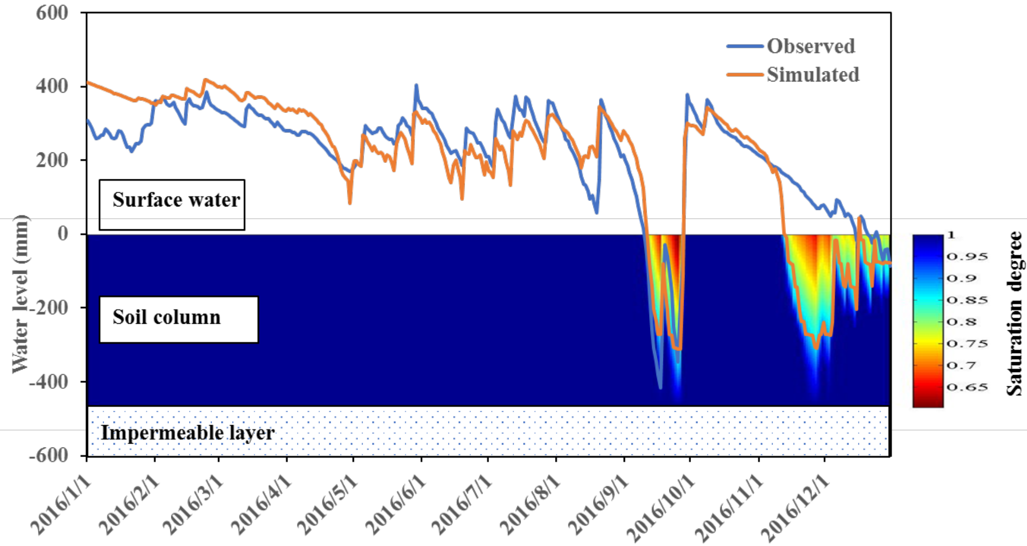


Observed *vs.* simulated daily water level for the natural wetland at Site #2 from 2016 to 2017.

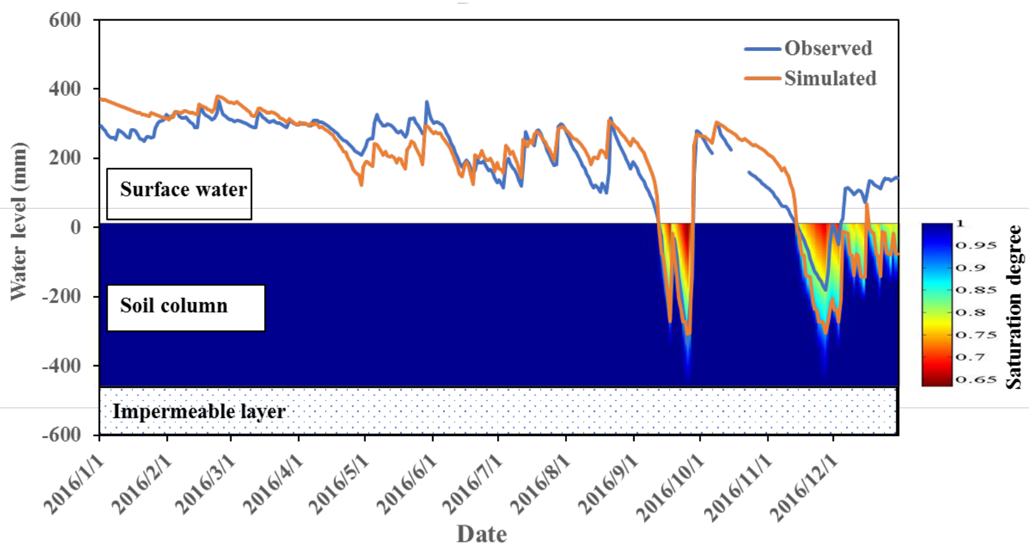


Wetland module evaluation for wetlands with impermeable layer

Observed *vs.* simulated daily water level for the restored wetland at Site #1 in 2016.



Observed *vs.* simulated daily water level for the nature wetland at Site #1 in 2016.



D3: Coupled terrestrial-aquatic carbon cycling

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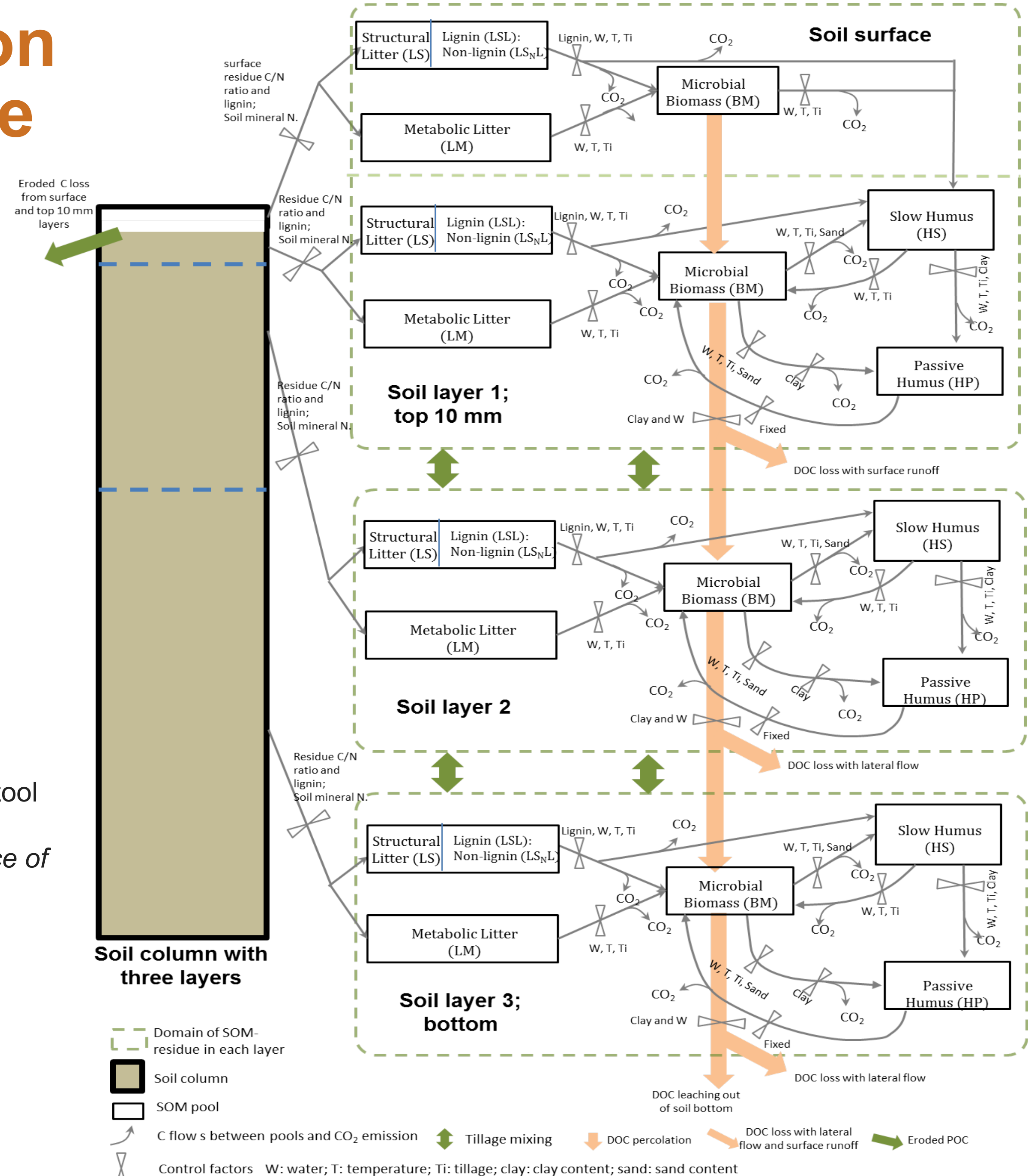
Terrestrial carbon module structure

- Schematic representation of new SOM-residue dynamics in SWAT.

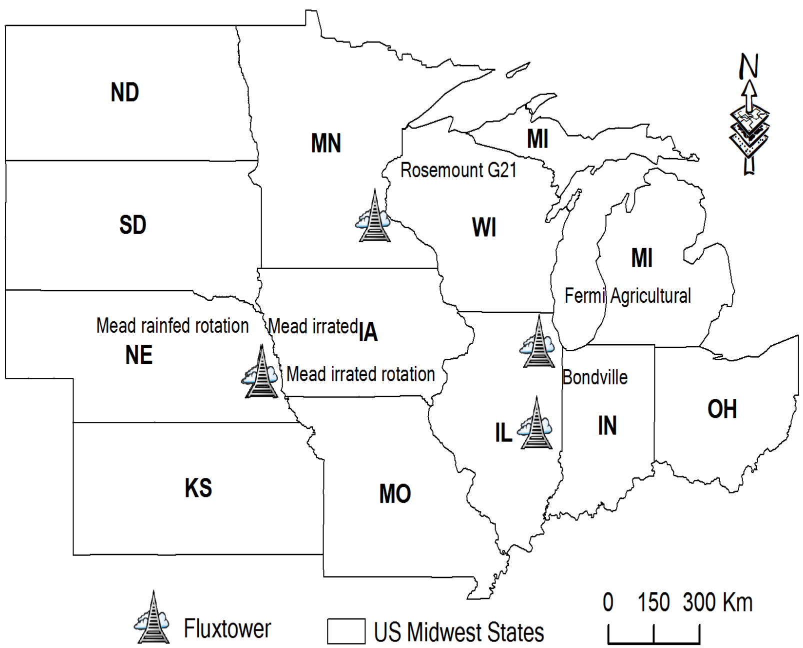
- Algorithms are derived from EPIC, CENTURY, and DSSAT.

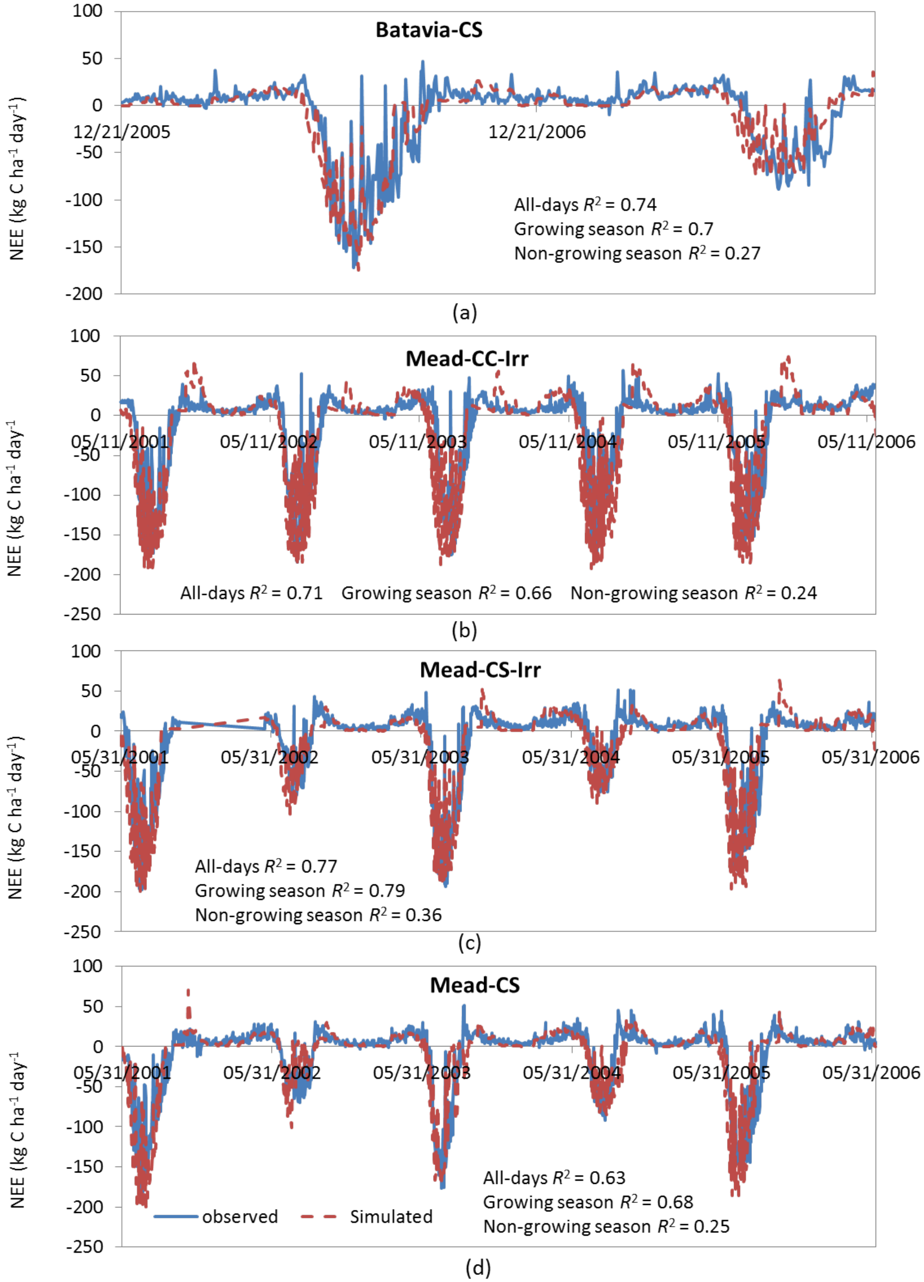
Zhang, X., Izaurralde, R.C., Arnold, J.G., Williams, J.R. and Srinivasan, R., 2013. Modifying the soil and water assessment tool to simulate cropland carbon flux: model development and initial evaluation. *Science of the Total Environment*, *463*, pp.810-822.

Zhang, X., 2018. Simulating eroded soil organic carbon with the SWAT-C model. *Environmental Modelling & Software*, *102*, pp.39-48.



Cropland carbon fluxes at six AmeriFlux towers

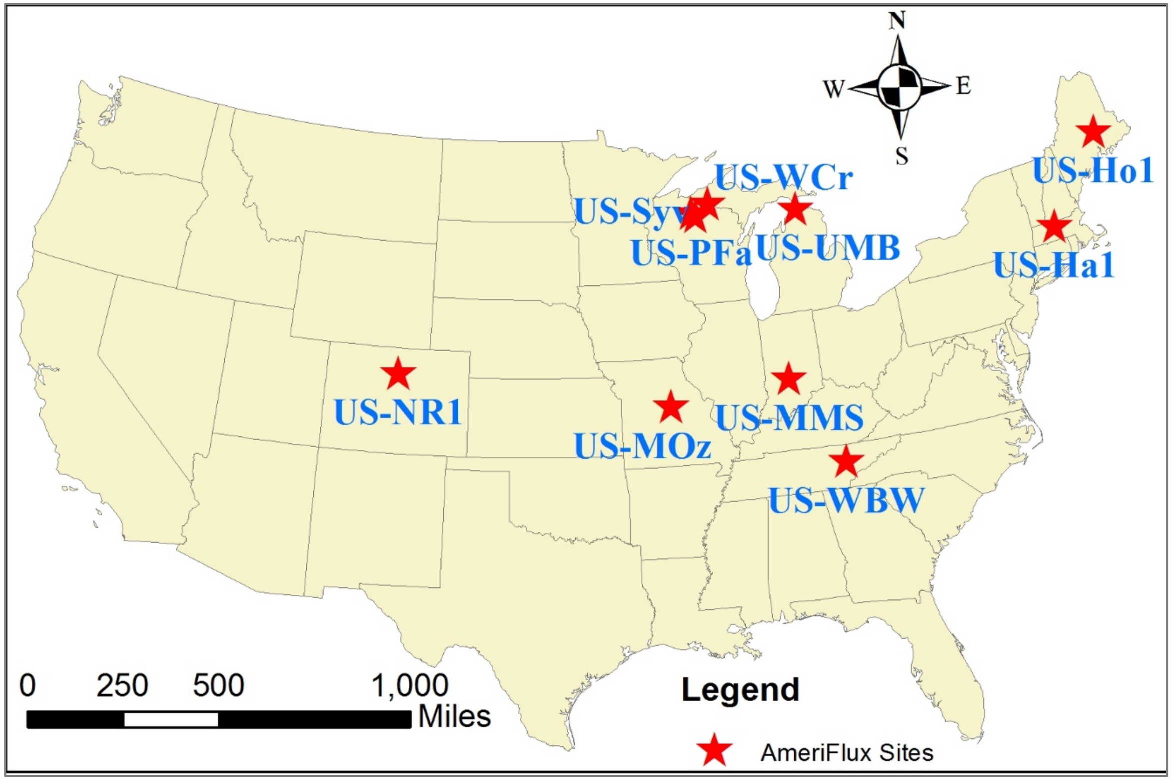




Comparison of SWAT simulated and flux tower observed Net Ecosystem Exchange

Forest growth and carbon balance

6 deciduous forest sites, 2 evergreen sites, and 2 mixed sites



Location of ten selected AmeriFlux sites for model performance evaluation (US-Ha1: Harvard Forest; US-Ho1: Howland Forest Main; US-MMS: Morgan Monroe State Forest; US-Syv: Sylvania Wilderness; US-UMB: UMBS; US-WCr: Willow Creek forest; US-MOz: Missouri Ozark; US-WBW: Walker Branch; US-NR1: Niwot Ridge; US-PFa: Park Falls)

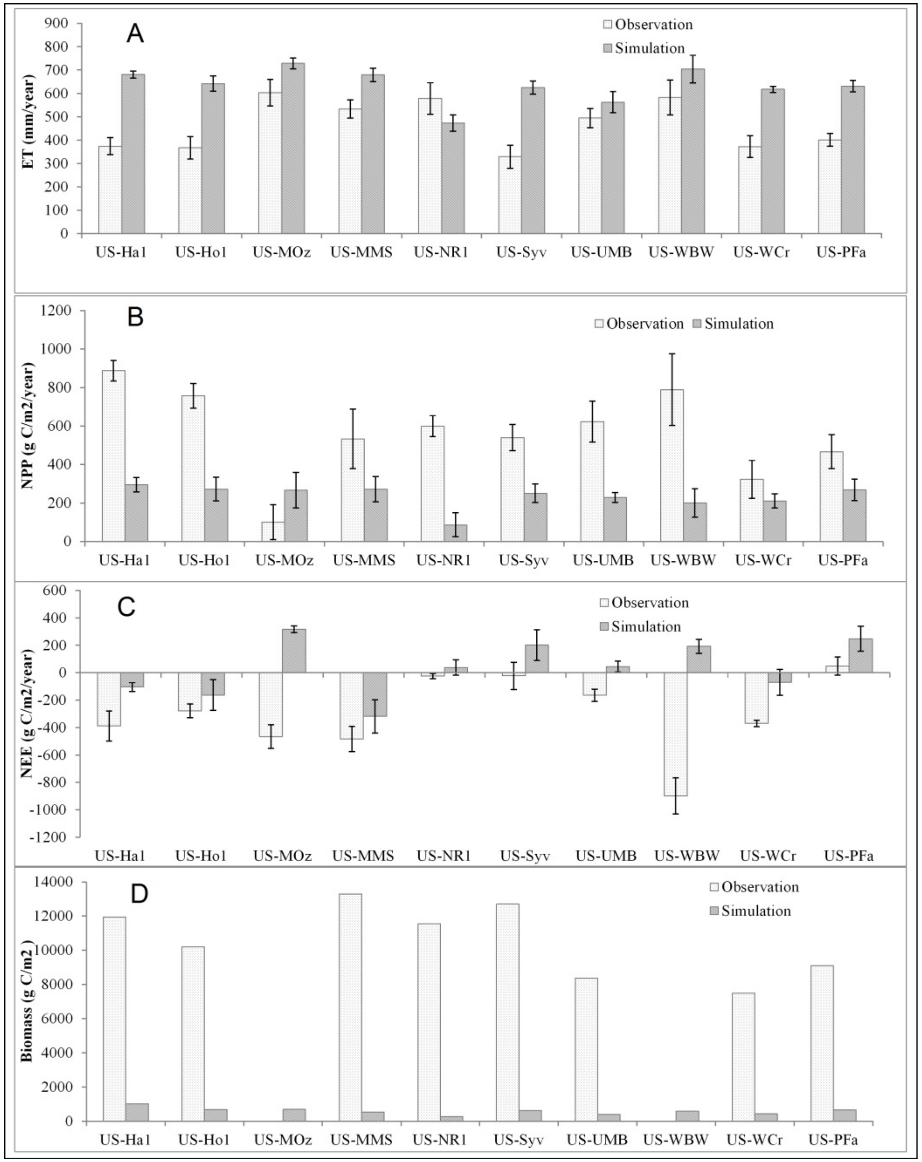
Parameter calibration of SWAT built-in forest module

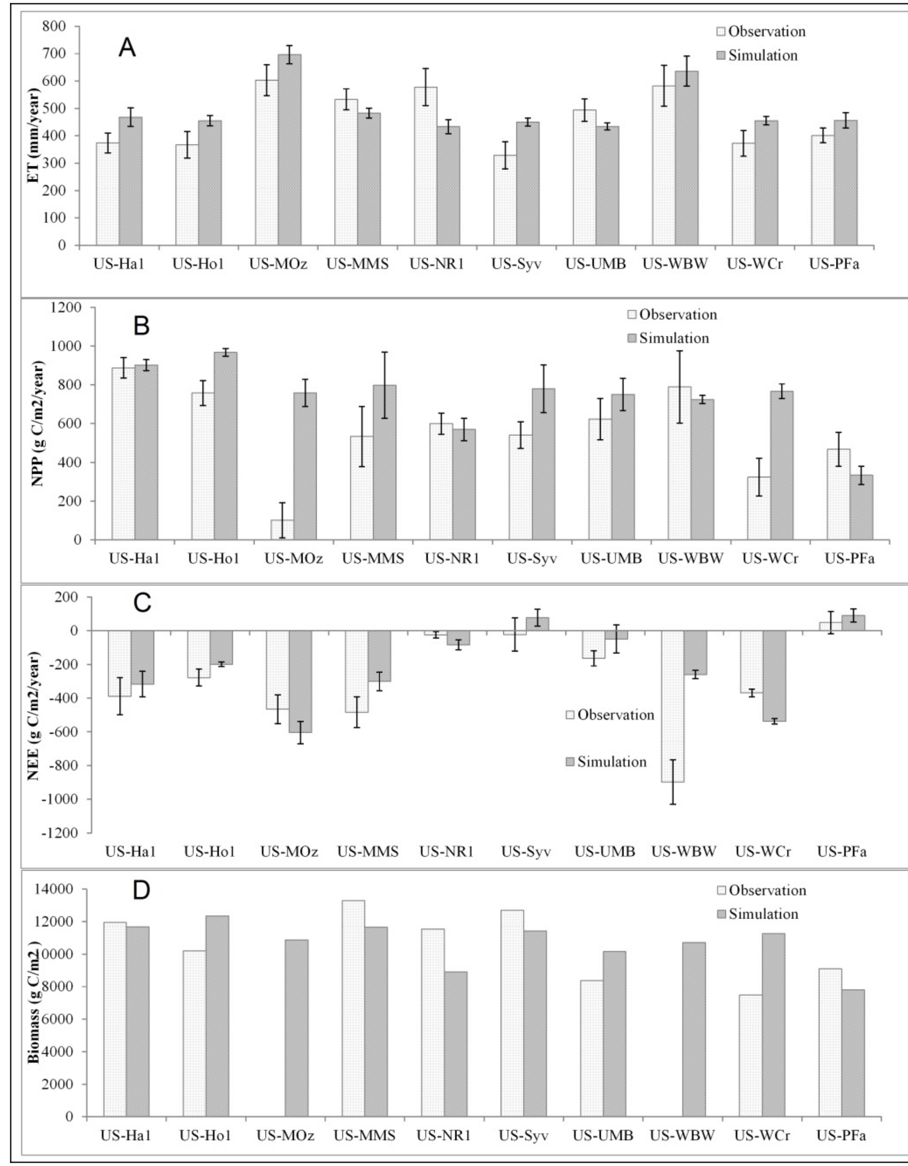
Parameter	Name	Unit	Default values			Calibrated values		
			FRST	FRSD	FRSE	FRST	FRSD	FRSE
BIO_E	Radiation use efficiency	kg biomass /ha/(MJ/m^2)	15	15	15	24-27 (25.5)*	26-30 (28.2) *	16-18 (17) *
BLAI	Maximum Leaf area index	unitless	5	5	5	4-5 (4.5)*	4-5 (4.6)*	3-4 (3.5)*
T_OPT	Optimum temperature	Degree (ºC)	30	30	30	25 (25)*	23-25 (24)*	20-25 (22.5) *
T_BASE	Base temperature	Degree (ºC)	10	10	0	10 (10) *	10 (10)*	0 – 5 (2.5) *
BIO_LEAF	Leaf to biomass fraction	unitless	0.3	0.3	0.3	0.02-0.05 (0.035)*	0.02-0.06 (0.033) *	0.015-0.025 (0.02)*

Calibrated parameters are consistent with previous studies, including Hilker et al., (2012); Schwalm et al. (2006); Zhu et al.(2006); Guo et al. (2015)

Yang, Q. and Zhang, X., 2016. Improving SWAT for simulating water and carbon fluxes of forest ecosystems. *Science of the Total Environment*, *569*, pp.1478-1488.

Performance of SWAT built-in forest module: default vs. calibrated parameters





Default parameters

Calibrated parameters

Since 1965

SWAT-N2O module based on DayCent and model test at Kellogg Biological Station, MI

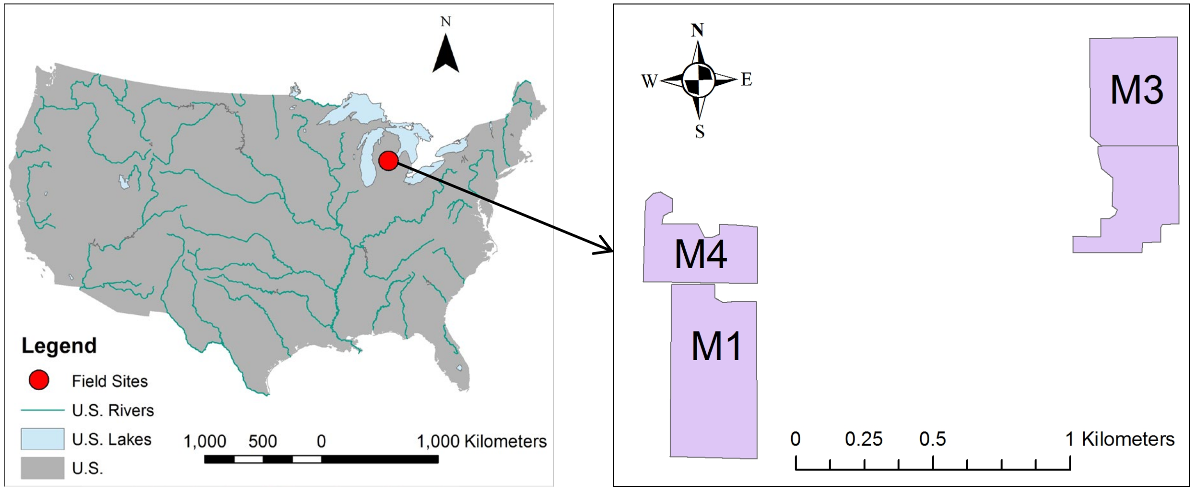
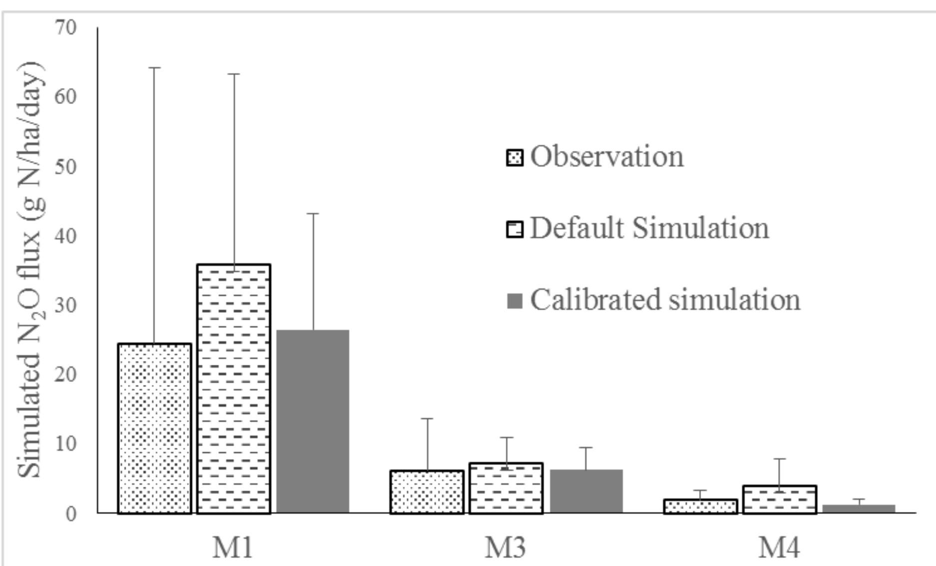


Figure 1. Locations of the three GLBRC scale-up experiment sites

A Corn site (M1), a switchgrass site (M3), and a reference site (M4) in the Marshall Farm Scale-up fields of GLBRC were selected for this study.



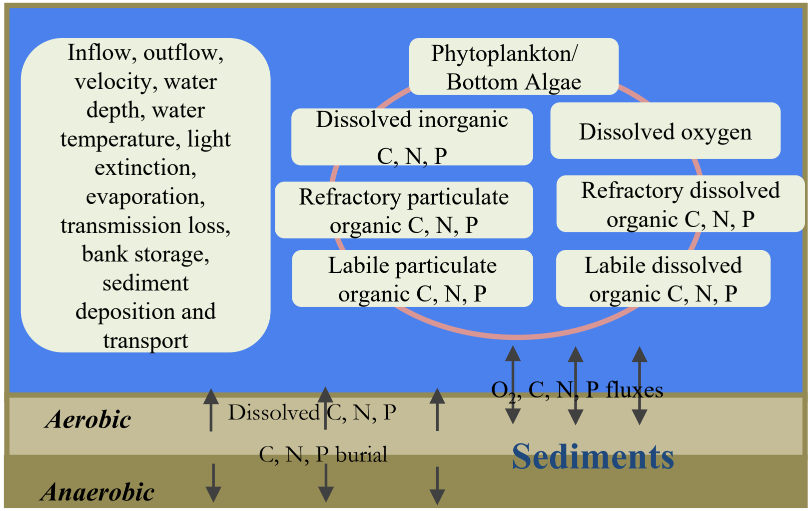
Del grosso, S., D. S. Ojima, W. J. Parton, E. Stehfest, M. Heistemann, B. De angelo, and S. Rose. 2009. Global scale DAYCENT model analysis of greenhouse gas emissions and mitigation strategies for cropped soils. Global and Planetary Change 67:44–50.

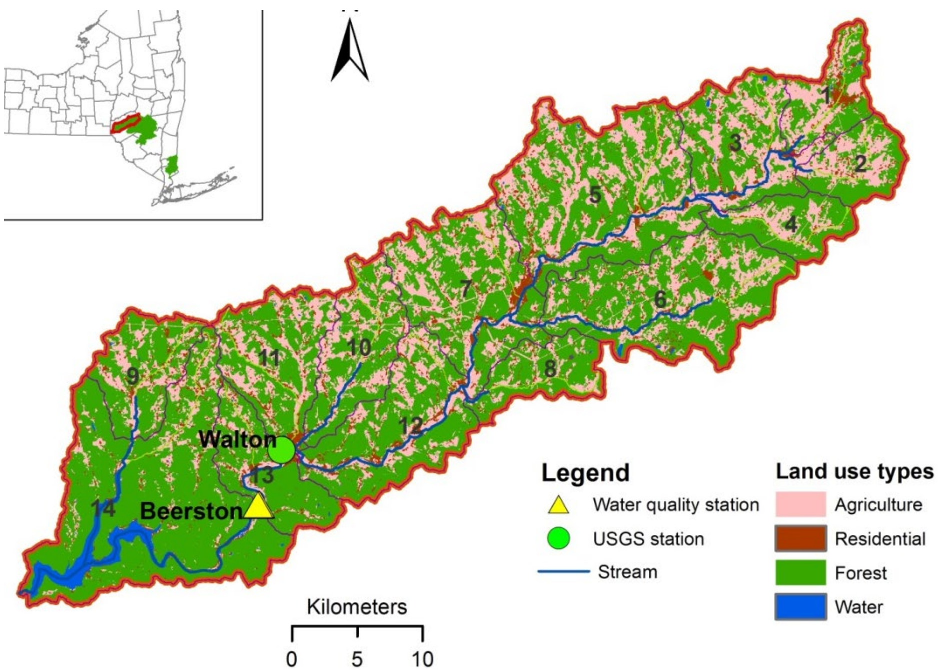
Yang, Q., Zhang, X., Abraha, M., Del Grosso, S., Robertson, G. P., & Chen, J. (2017). Enhancing the soil and water assessment tool model for simulating N2O emissions of three agricultural systems. *Ecosystem Health and Sustainability*, *3*(2), e01259.

Aquatic carbon cycling in SWAT

Ongoing development of an aquatic carbon cycling algorithm based on QUAL2K (Chapra et al. 2003) and CE-QUAL-W2 (Cole and Wells 2006), which was tested in the Cannonsville watershed and captured well daily DOC fluxes at the watershed outlet

Aquatic ecosystems





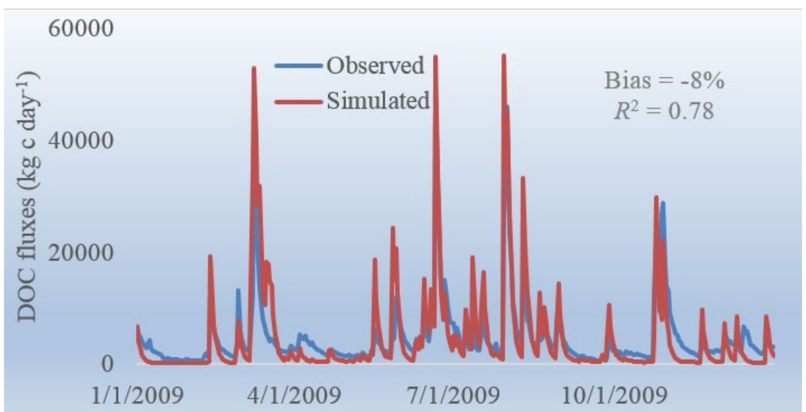
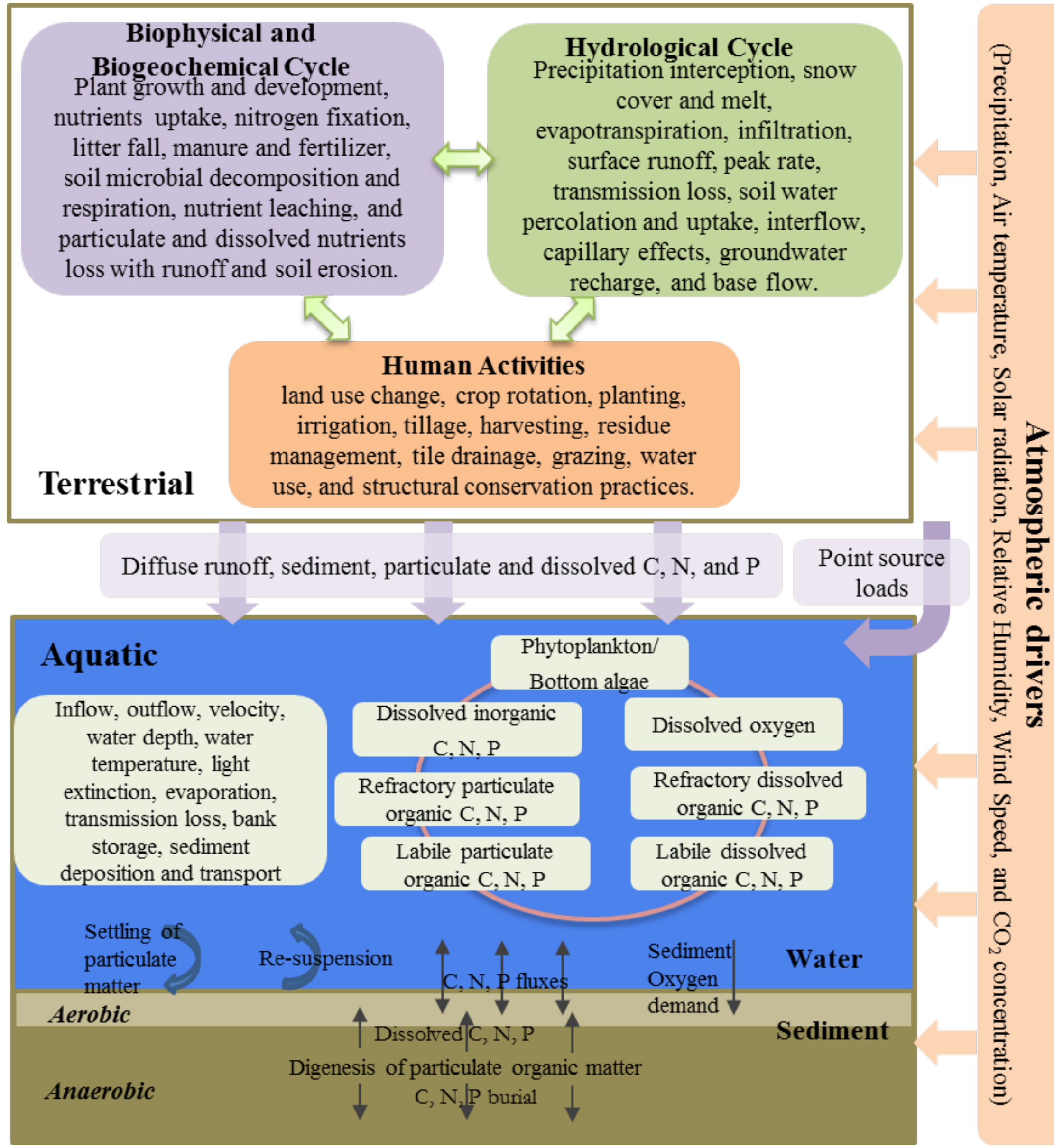


Illustration of the capability of the aquatic carbon module within SWAT for simulating DOC fluxes near the outlet of the Cannonsville watershed.

Coupled terrestrial-aquatic carbon cycling

- Carbon cycling in river networks is relevant to the fate of ***2-6*** Pg C yr^{-1}.
- Lacking reliable quantification of the aquatic carbon balance.



Next Steps

- Terrestrial carbon module is available in the latest SWAT model code since 2016, and Jeff Arnold and Nancy Sammons have incorporated the code into SWAT-Plus for testing.

- More examination and evaluation of the soil water and forest growth modules and deliver to released SWAT version.

- Continue development and testing of aquatic carbon cycling.

Thank you for your attention!

D2: Soil temperature and freeze-thaw cycle

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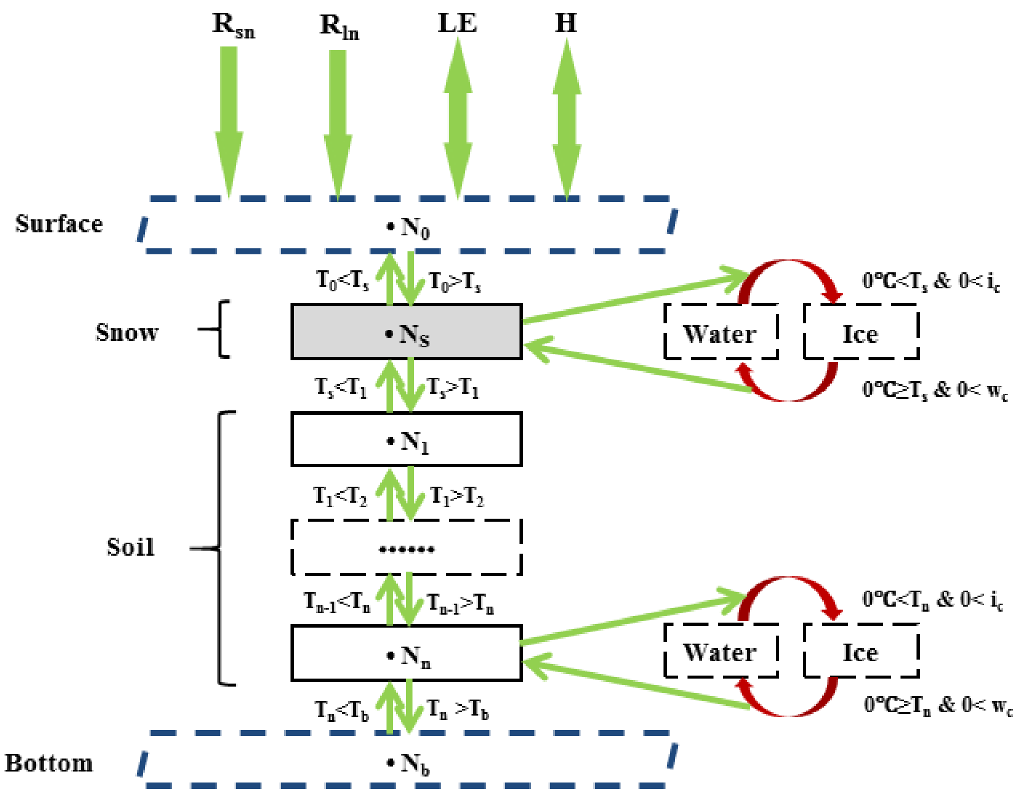
Physically based soil temperature and energy balance module



A physically-based soil temperature module was developed based on heat transfer theory in snow and soil layers described as in Yin and Arp (1993):

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\frac{k}{C} \cdot \frac{\partial T}{\partial x}\right)\frac{s}{C}$$

where *T* is the temperature, *t* represents the time step (in days), *k* is the thermal conductivity, *C* is the volumetric heat capacity, *x* is the vertical distance from the air-soil or air-snow interface, and *s* is the latent heat source/sink term.

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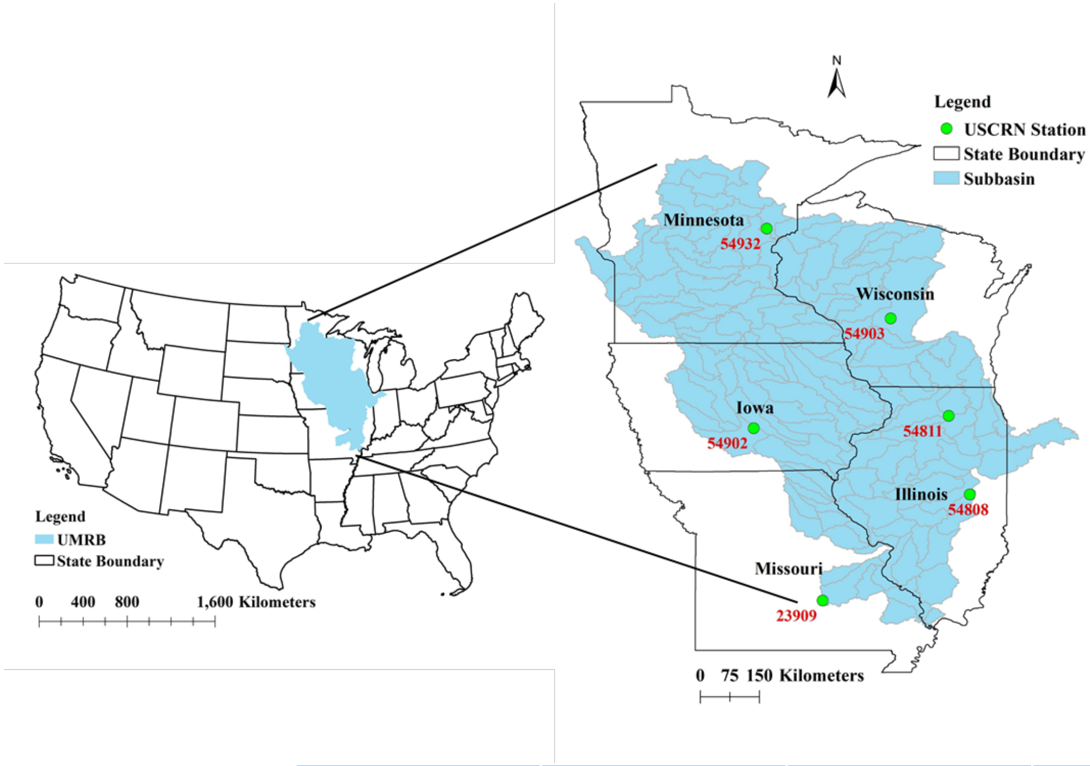
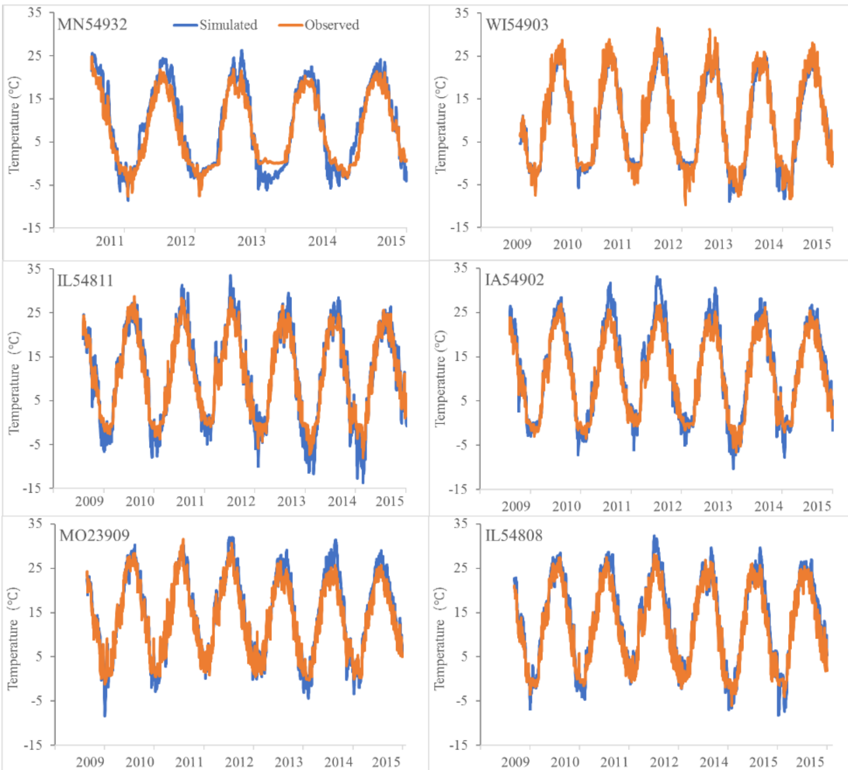
Field experimental sites for model evaluation



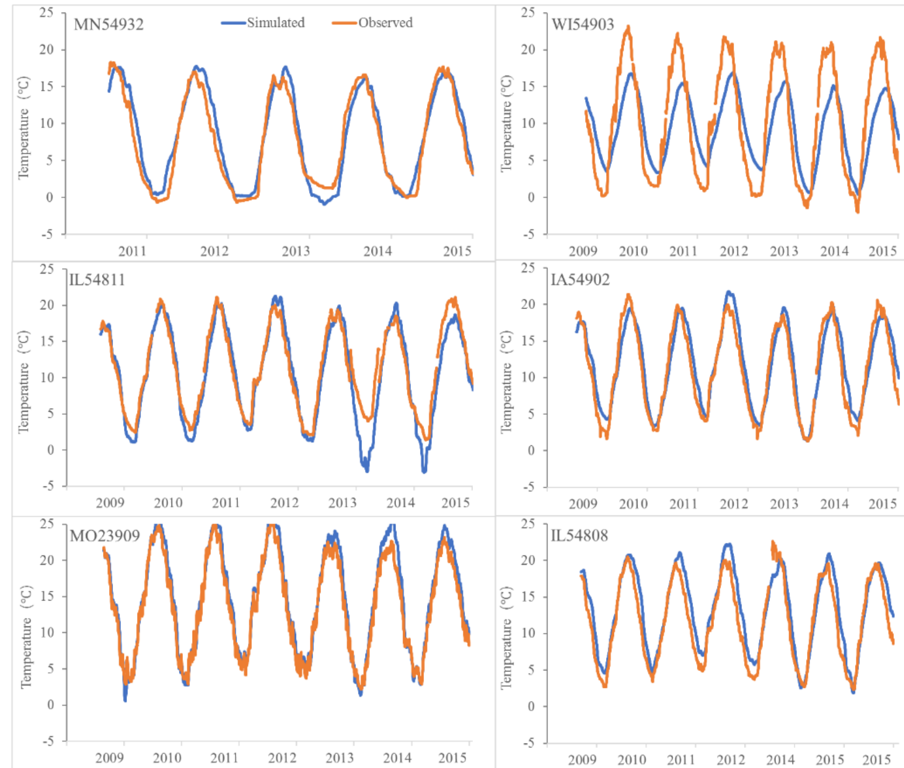
Daily surface and soil temperature records at 5, 10, 20, 50, and 100 cm depths derived from six stations of the NOAA's U.S. Climate Reference Network (USCRN) within the Upper Mississippi River Basin.

State	Station ID	Subbasin	Slope (%)	Data Used
MN	54932	30	0-2	2011-2015
WI	54903	56	0-2	2009-2015
IL	54811	81	0-2	2009-2015
IA	54902	90	0-2	2009-2015
MO	23909	121	0-2	2009-2015
IL	54808	128	0-2	2009-2015

Simulated vs. observed soil temperature



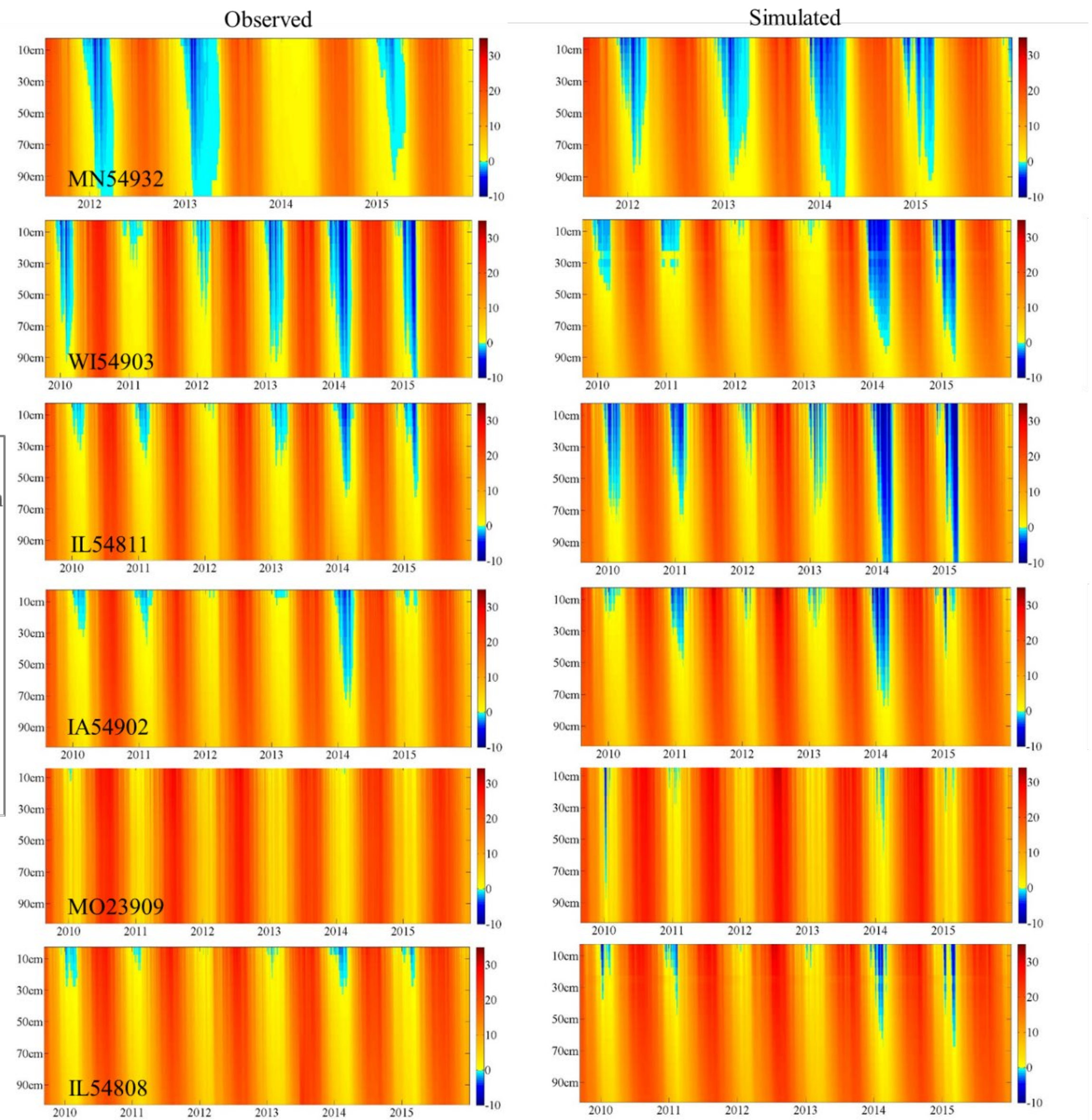
Simulated vs. observed soil temperature at 5 cm depth at six USCRN stations.

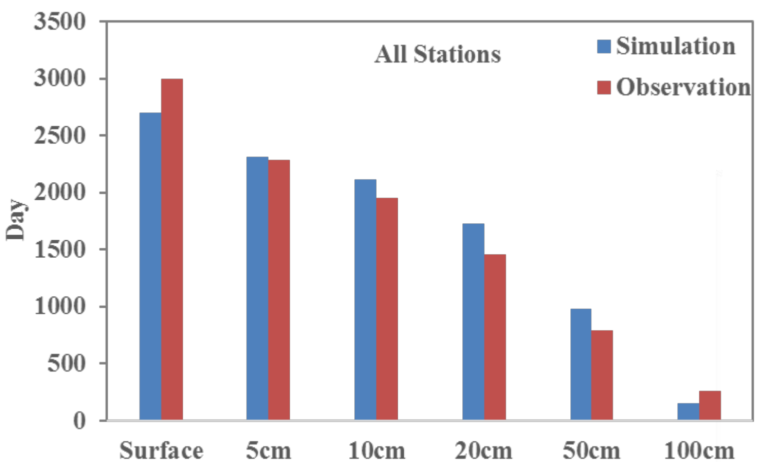


Simulated vs. observed soil temperature at 100 cm depth for the six USCRN stations.

Model assessment for freeze-thaw cycle and frozen depth

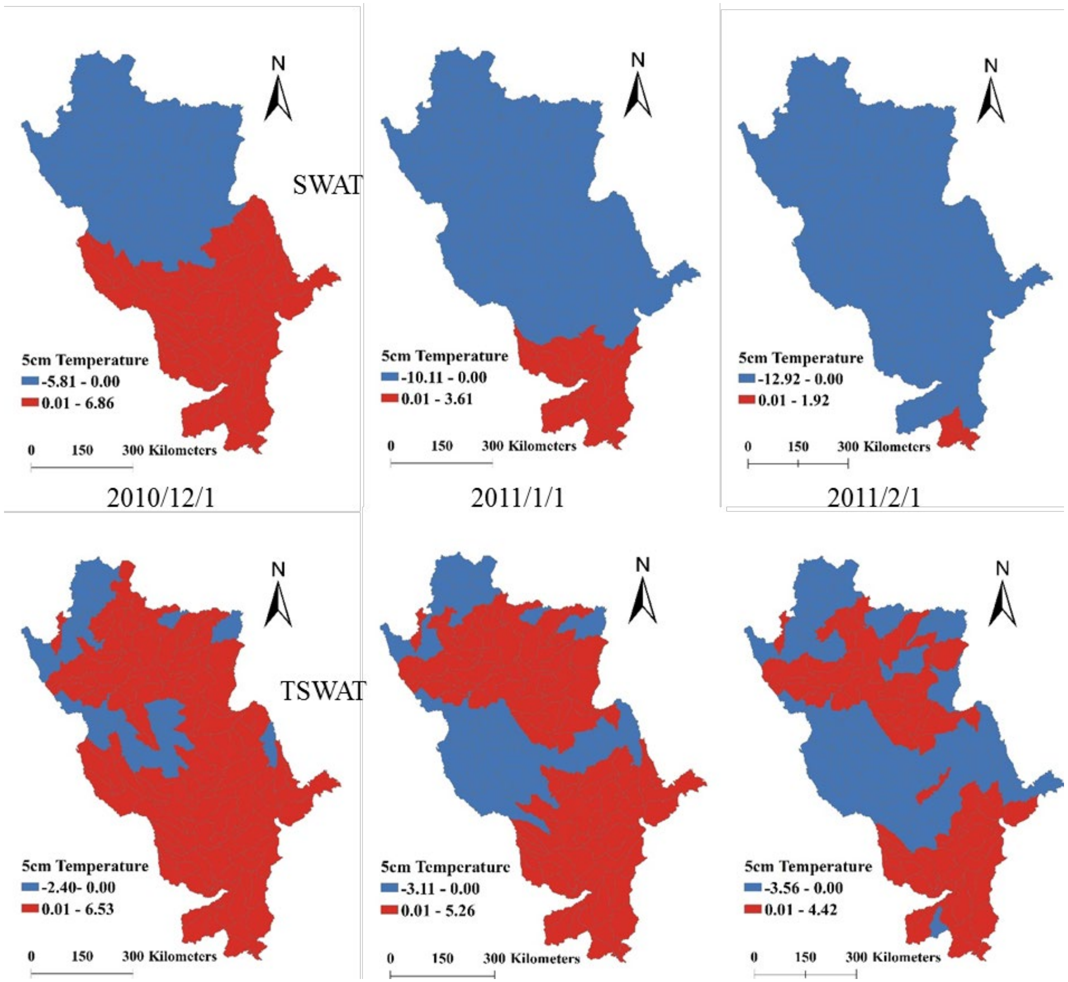
Simulated vs observed frozen (temperature ≤ 0 ℃) depth at the six USCRN stations. Left vertical axis is in ℃.



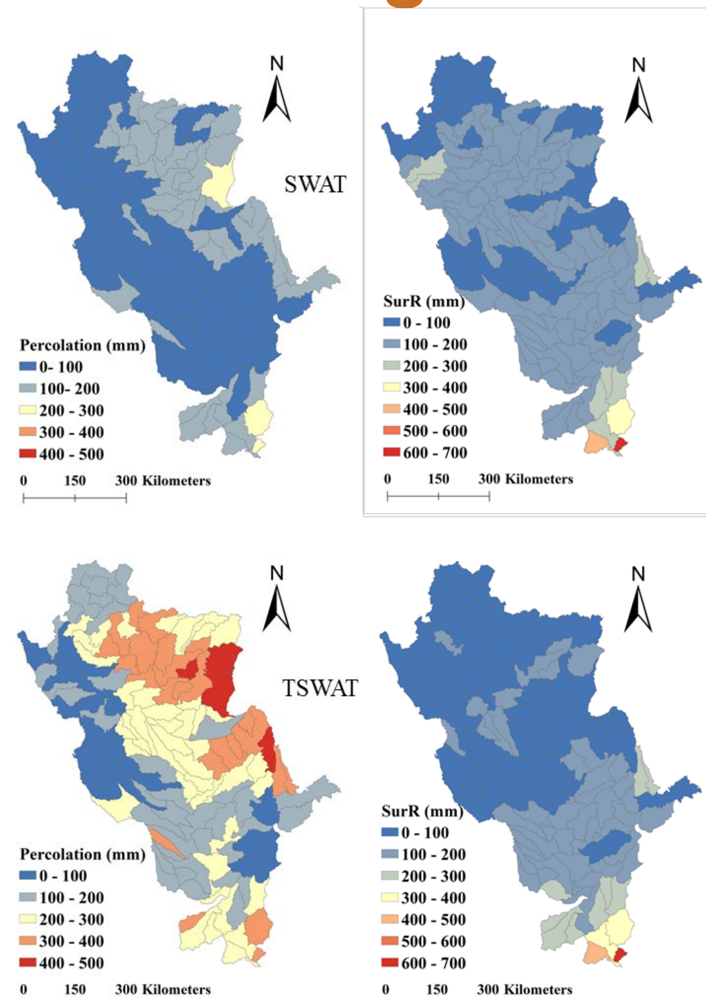


Simulated vs observed frozen (temperature ≤ 0℃) days for surface and soil layers at different depths

Implications of freeze-thaw cycle representation for hydrologic modeling



Simulated mean 5 cm soil temperature for subbasins of UMRB in five reprehensive days of 2011 by the TSWAT and SWAT



Simulated percolation, surface runoff (SurR), and in the UMRB by TSWAT and SWAT in 2011.