Impact of Projected Biofuel Production on Water Use and Water Quality

Technology Area Review:
Sustainability
WBS: 11.1.1.1

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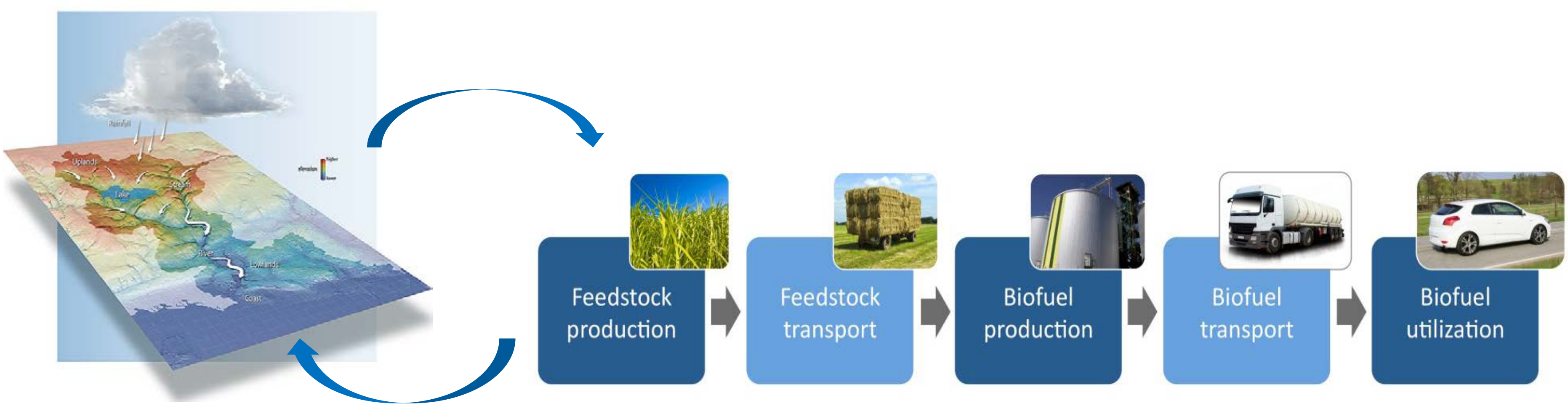
Argonne National Laboratory

May 22, 2013

Goal Statement

Develop analyses for water use in the production of cellulosic and advanced biofuel and determine its impact on regional water quality and resource; support programmatic decisions by establishing quantitative metrics as a basis for enabling sustainable industry growth and thereby reduce U.S. reliance on petroleum oil.



Quad Chart Overview

Timeline

- Project start date: FY07
- Project end date: Project continuation and direction determined by DOE annually
- Percent complete: 40% (FY13)

Barriers

- **St-A**. Scientific consensus on bioenergy sustainability
- **St.-C**. Sustainability data across the supply chain
- **St-D**. Indicators and methodology for evaluating and improving sustainability

Budget

- Funding for FY11 ($700K)
- Funding for FY12 ($595K)
- Funding for FY13 ($550K)
- Years the project has been funded: 7; average annual funding: $400K.

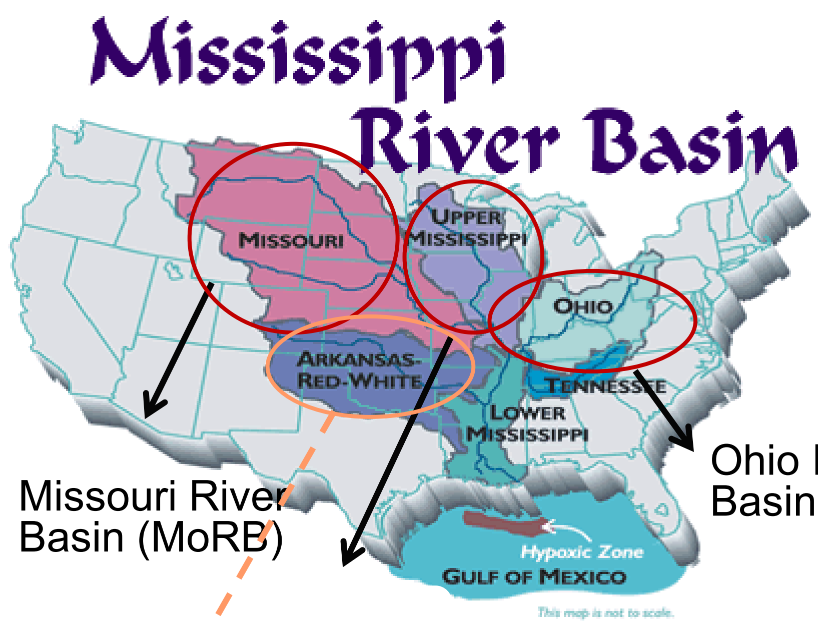
Partners

- Interactions/collaborations:
  - U.S. Army Corp. Engineers
  - ORNL (Y. Jager), PNNL (L. Snowden-Swan), Purdue University (I. Chaubey)
- Project management
  - Define milestones in Annual Operation Plan, monthly progress reports, and calls; schedule deliverables

Definitions

- **Water footprint (WF)** – Net water loss to evapotranspiration and evaporation; incorporation of water into products or solids by a production process or activity
- **Evapotranspiration (ET) –** Loss of water from the land cover both by evaporation from the soil surface and by transpiration from the leaves of the plants growing on it
- **RO –** Runoff flow
- **SWAT –** Soil Water Analysis Tool, a hydrologic watershed model
- **Water withdrawal –** Water uptake from surface or groundwater
- **Water consumption** or **Water use –** Water loss (*accounted for in WF)*
- **Blue water** – Surface and ground water
- **Green water** – Soil moisture from rainfall that used by vegetation
- **Grey water footprint** – Volume of wastewater and water required to dilute the chemicals in the wastewater to an acceptable level of concentration for the water body (specific to the WF methodology)
- **Blue Water Use Index –** A measure of the impact on water resource. Calculated as the blue water demand for the production of biofuel in its feedstock and refinery stages as percentage of total available precipitation in a region.

Project Overview



Missouri River Basin (MoRB)

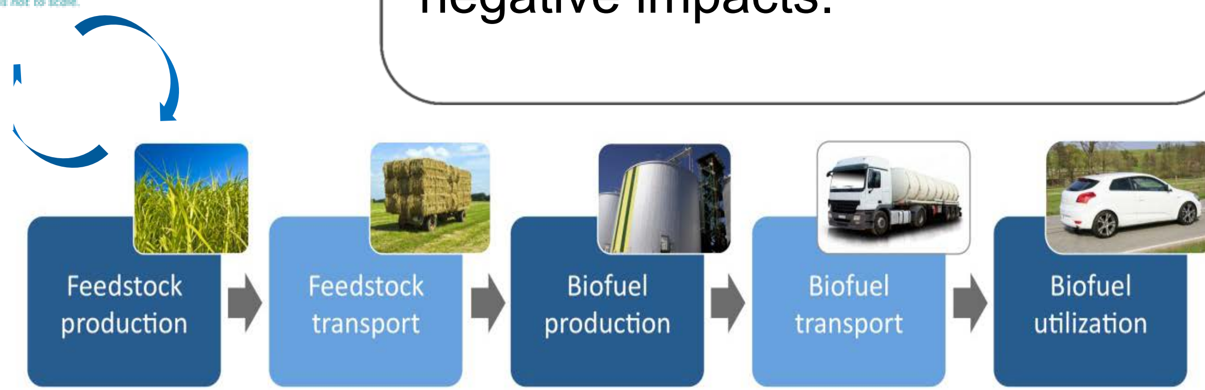
Ohio River Basin (ORB)

Upper Mississippi River Basin (UMRB)

ORNL

Objectives

Develop analytical framework and tool to quantify the relationships between bioenergy production and **water use**, **water quality,** and **water resource** availability; identify region-specific scenarios that are able to increase water-use efficiency and reduce potential negative impacts.



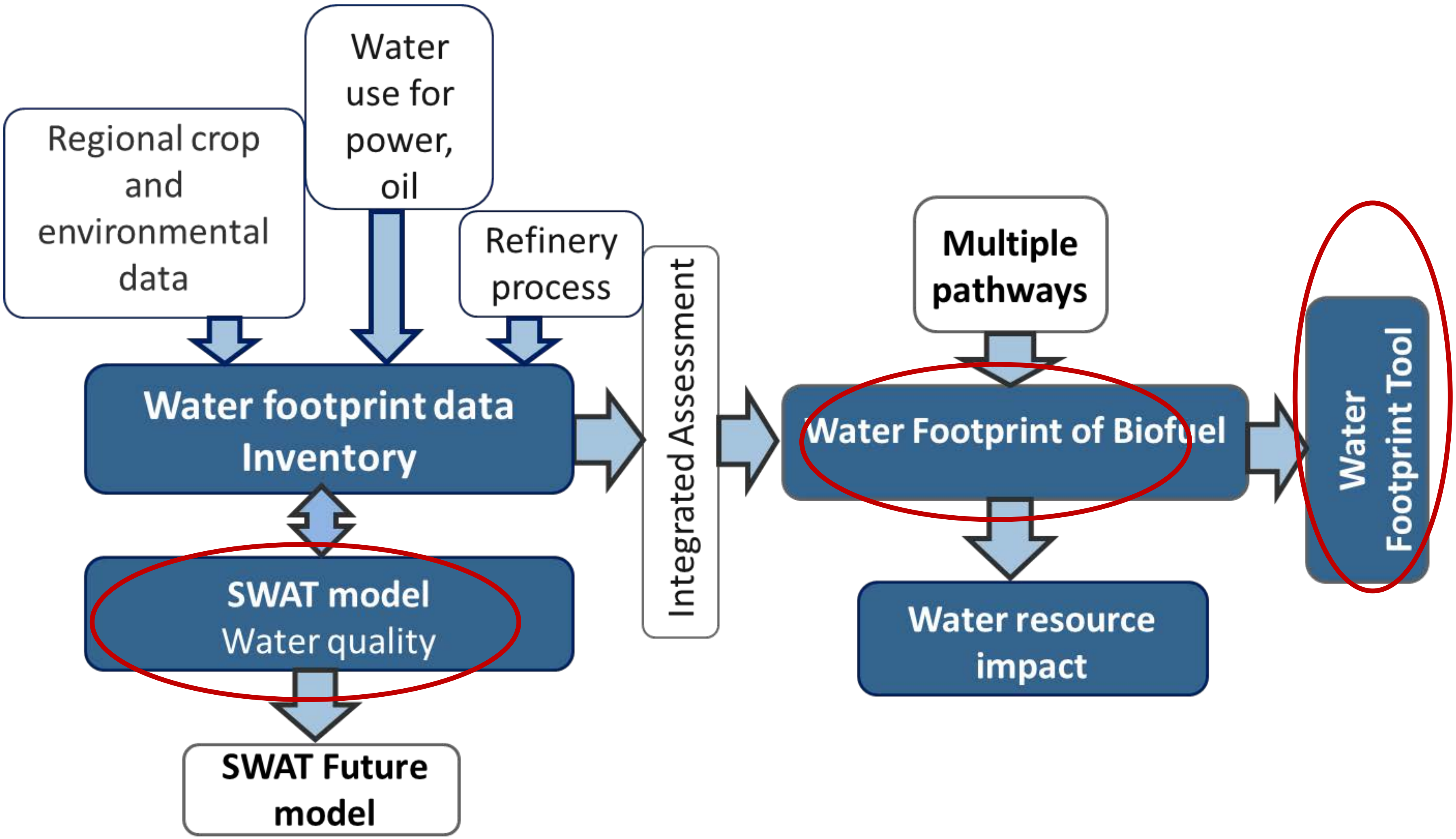
Project Overview – Cont.

- Commenced in 2007
- Considers water consumption across biofuel production supply chain with a focus on feedstock production and refinery
- Estimates regional water footprint of cellulosic biofuels from agricultural residue, perennials, and forest resources, algae biofuel.
- Addresses water quality in tributary basins of Mississippi river basin by developing watershed models.

Key Aspects

- Consistent **methodology** that is tailored to bioenergy feedstock application
- Spatial-explicit water analysis for various biofuel pathways at **county or watershed scale** to address spatial heterogeneity
- Comprehensive water **data inventory** across feedstock production and refining stages

1 – Approach: Analysis Framework



1 Approach

- Project team:

  Y. Chiu, Natural Resources, *Y. Demissie, Hydrology*

  S. Yalamanchili, Engineering, *E. Yan, Geology*

  D. Lampert, Engineering

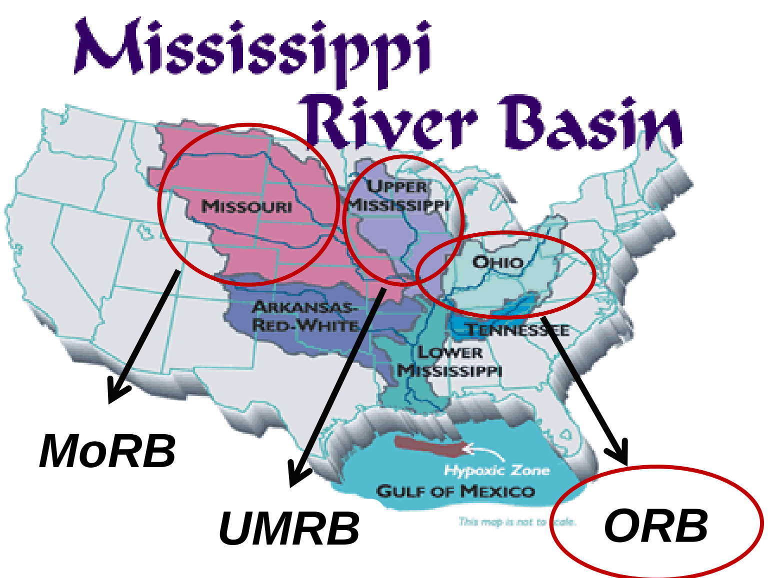
- Collaboration
  - *Sharing modeling approach and/or data: Army Corp Engineers, Yetta Jager (ORNL), Indrajeet Chaubey (Purdue)*
  - *Process water sample: Lesley Snowden-Swan (PNNL)*
- Adopt WF methodology (UNESCO, ISO development); received training and certificate at Water Footprint Network
- Develop major assumptions in consultation with USGS, USFS, biofuel industry; data source: government reports/open literature
- Calibrate and verify assessment results with field observations
- Management:
  - Define **key milestones** – SWAT base model, WF of cellulosic pathway, WF tool; deliver **briefings** to BETO (May 2013, Sept., July, and Jan. 2012)
  - Potential **risks**: data screening and comparison and uncertainty analysis to address data availability and data quality issues

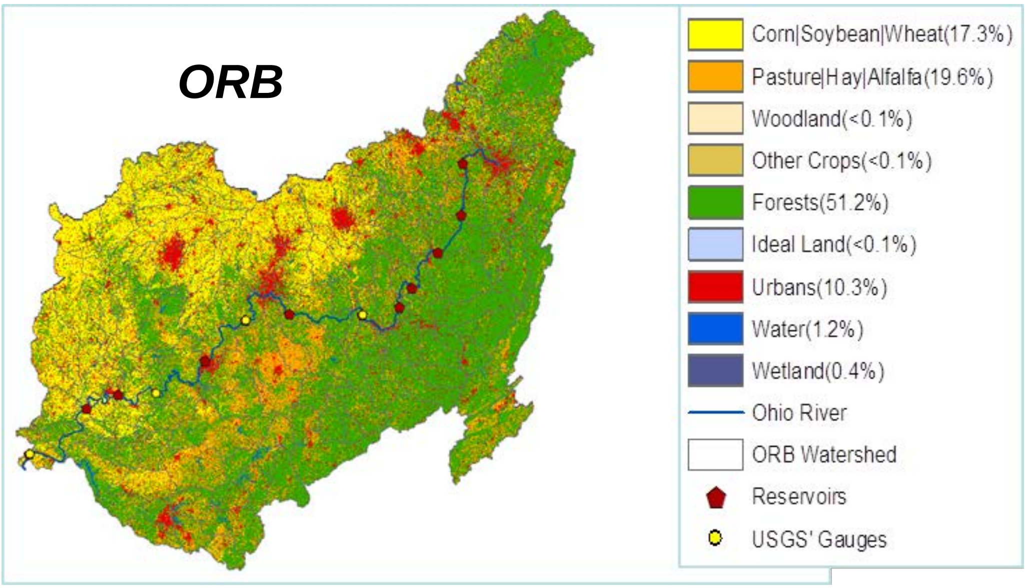
2 Technical Accomplishments: Overview

Supported by BETO since 2007, this project

- Developed a **comparative study** of blue water use for ethanol and petroleum (conventional, oil sands) production
- Examined blue water use in electricity generation (fossil, non-fossil, renewables)
  - **WEGM** v1.1 http://greet.es.anl.gov/index.php?content=power_water,
- Estimated water quality for Mississippi river basin by developing three **SWAT** models and analyzed water quality impact of BT2 scenarios
- Assessed county-level **water footprint** of biofuels (corn, soybean, corn stover, wheat straw, switchgrass, miscanthus, forest resource in U.S., and algae in southeast states)
- Developed water footprint tool
  - **WATER** http://WATER.es.anl.gov
- Quantified the range of regional water **sustainability indicators** for biofuels (corn, stover, soybean) in the UMRB and ORB and United States (*BETO Sustainability Platform 2012 Milestone Report*)

I. Develop SWAT Model





Key milestones

- UMRB, ORB, MoRB SWAT base models development
- BT2 scenario implementation on SWAT models

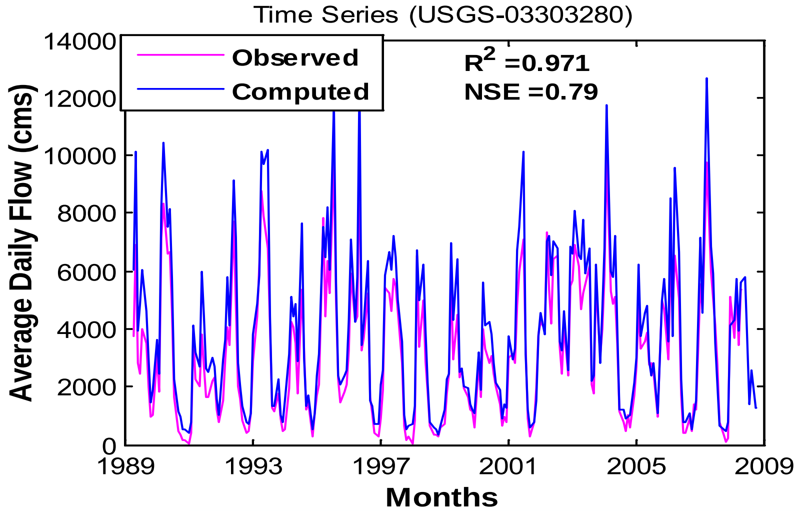
Status

- UMRB SWAT base model, multiple scenarios (100%) (2011 review)
- ORB SWAT base model, analysis, future scenarios (100%) *
- MoRB SWAT base model is under development (70%) *
- Two journal publications.

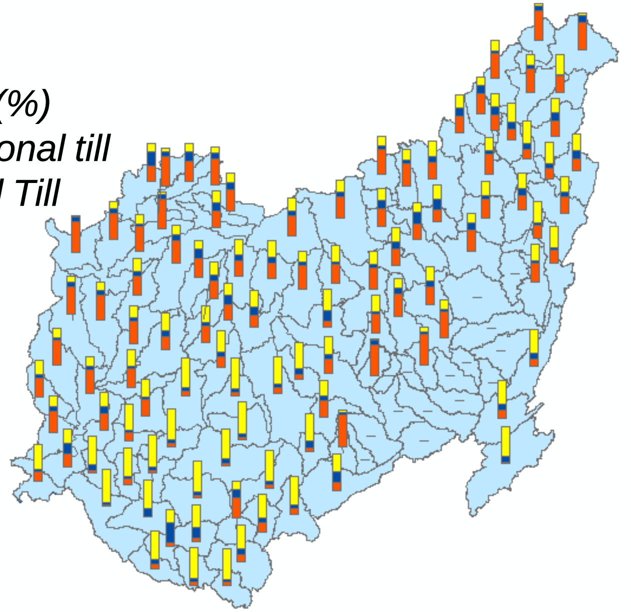
*** Conducted since last review**

SWAT Model Results Contribute to Development of Baseline and Future Water Sustainability Indicators

- Simulated **20-yr watershed processes**
- Incorporated **land use and water data**: Crop, fertilizer, and manure applications; tillage, tile drains, withdrawal for irrigation and by other sectors; point sources, reservoirs
- Extensive sensitivity analysis, calibration, and validation
- Simulated several management schemes and their impacts on **N, P, and SS loadings**;
- Applied statistics and derived sub-basin scale sustainability indicators (ORB and UMRB)

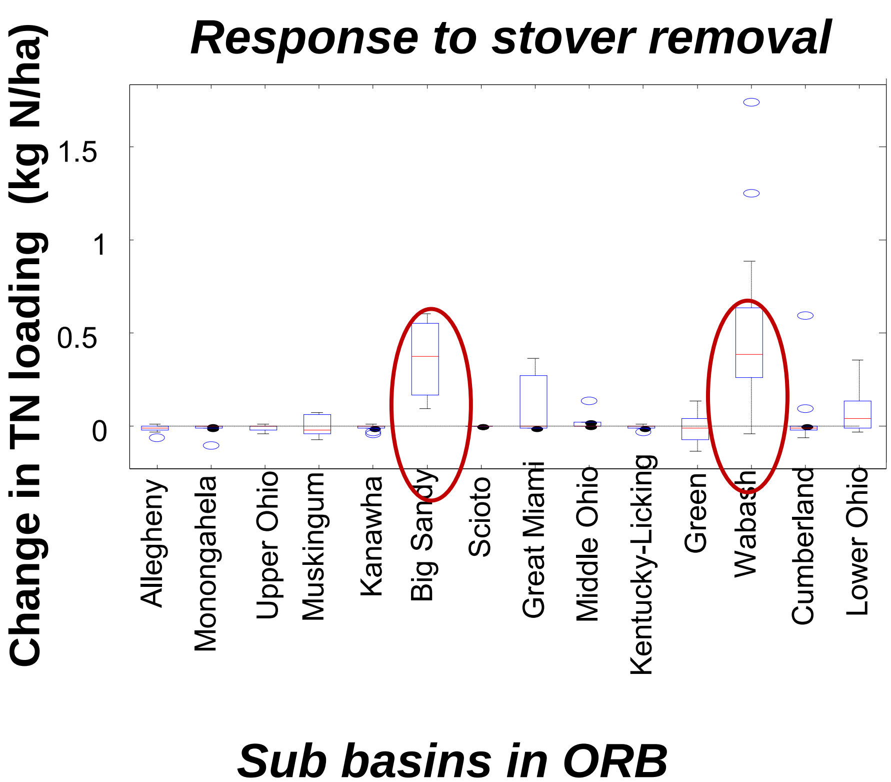


Tillage for corn (%)
Red – Conventional till
Blue – Reduced Till
Yellow – No till



SWAT Facilitates Analysis of Management/Practices

Understand the variability, magnitude, and spatial distribution of water indicators at different scales and their responses to a change



- Group 120 sub basins into 14 larger sub basins to conduct initial screen and followed by detailed analysis at the small sub basin scale
- Conduct sensitivity analysis by quantifying percent of change
- Identify sub basins that have shown strong response to a change in stover harvest, crop rotation, and fertilizer application rate.

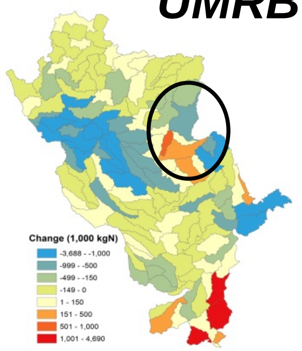
SWAT Enables Analysis of Future Production and Climate Impacts

- Increased production (UMRB, ORB)
  - BT2 USDA baseline, $50.00/d.t.
- Increased production with climate change (UMRB)
  - BT2 USDA baseline
  - Global climate model: A1B SRES
- Results mixed
  - ET ↑ RO ↓
  - N, P ↓↑ Sediment ↑↓

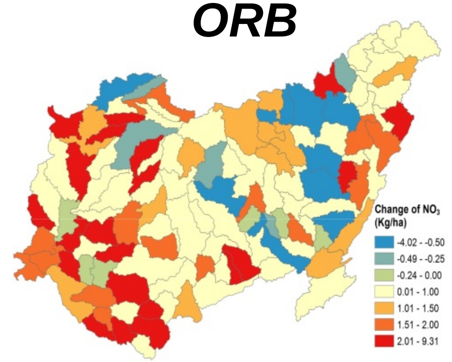
From baseline 2006 to 2022 BT2

Change of Nitrate Loadings

UMRB

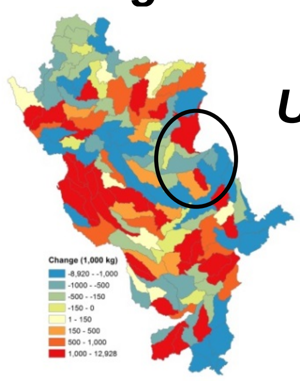


ORB



BT2 with response to climate change

UMRB



- Describe the *changes* in water quality and hydrologic cycle responding to increased production and climate change at sub basin level
- Identify potential hot spot and assist evaluating mitigation program that could reduce negative impact

II. Develop Water Footprint (WF)

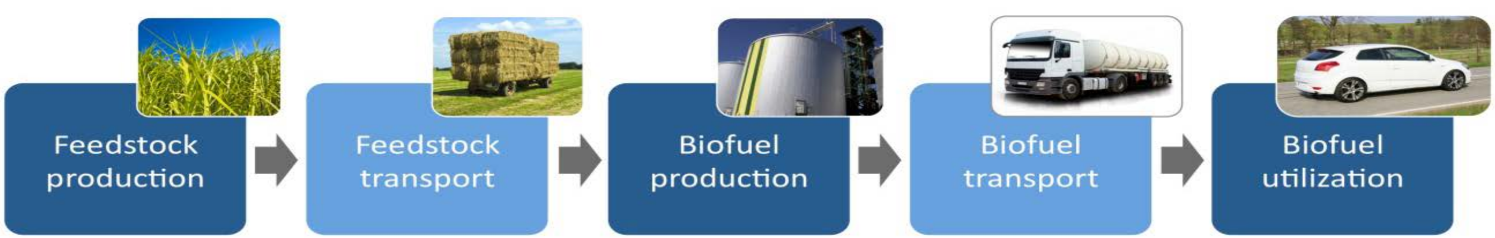
Key milestones

- WF of cellulosic biofuels in the U.S.
- Launch on-line WF tool

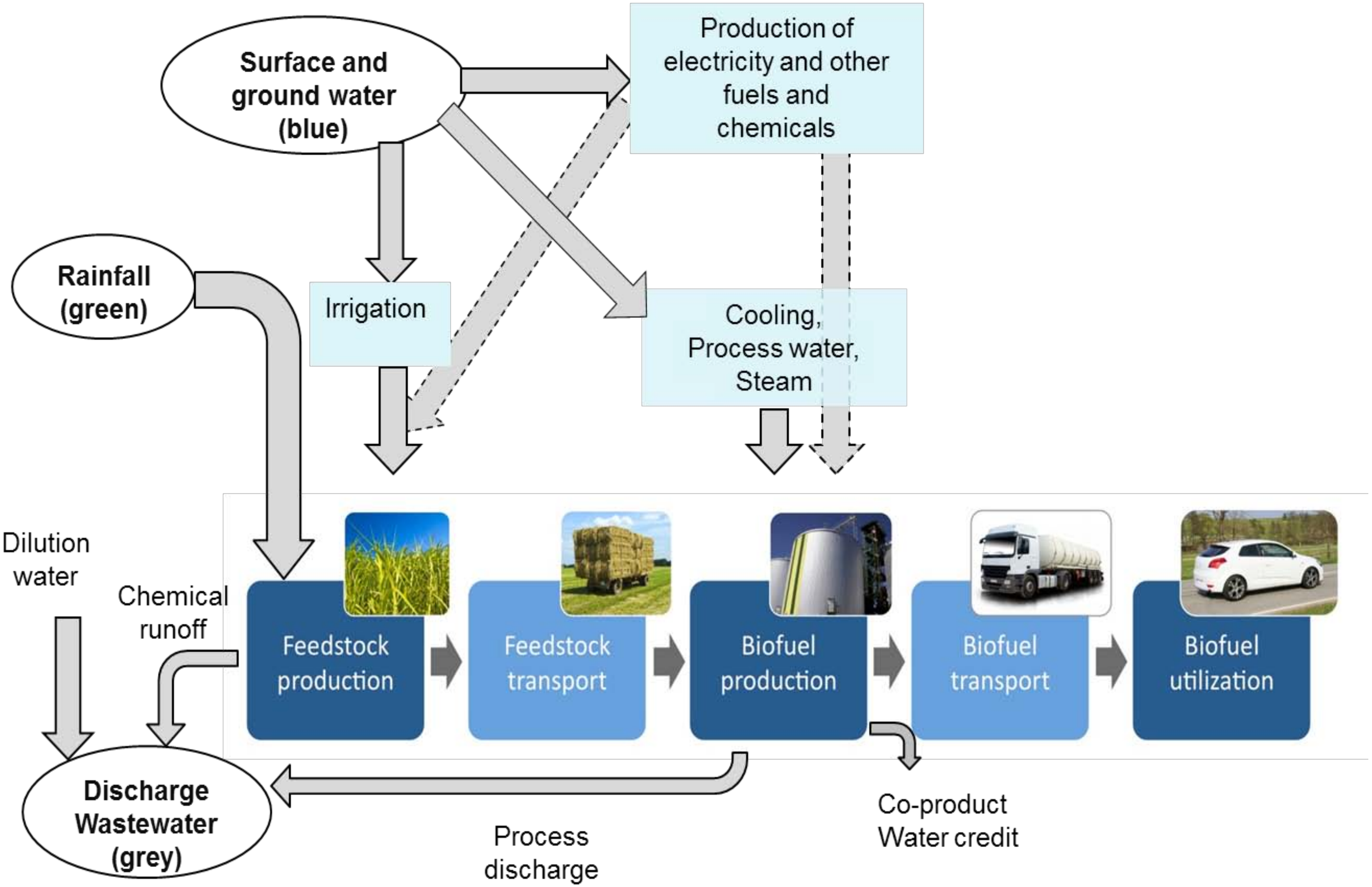
Status

- WF analysis
  - Corn, stover, soybean, wheat straw-biofuels*, SWG*, MXG* (100%);
  - Municipal wastewater for algae in southern U. S.* (100%)
  - Forest wood* (70%)
- WF tool development
  - Corn, soybean, stover and wheat* (100%)
  - Perennial and forest wood* (20%)
- Four journal publications; Three webinars to stake holders (2012)

*** Conducted since last review**



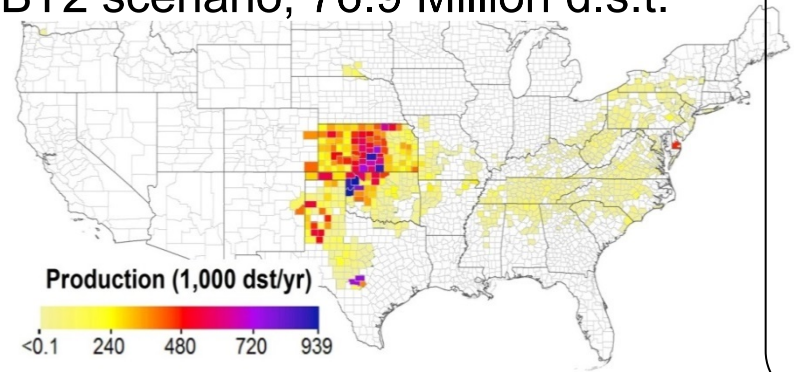
Water Footprint Accounting



Established Water Footprint (WF) for Perennial-based Biofuels

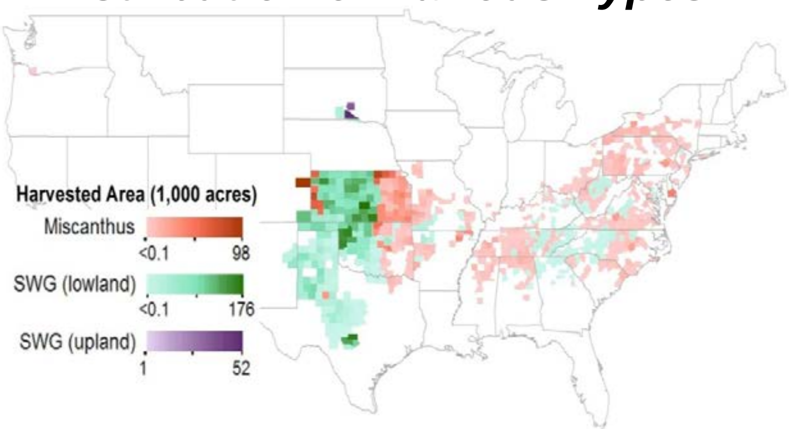
Spatial Distribution of Potential Perennial Feedstock

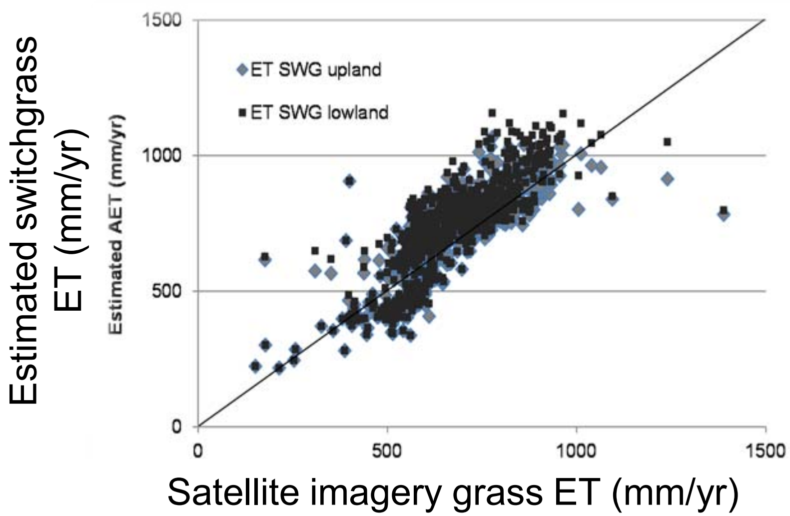
BT2 scenario, 76.9 Million d.s.t.*



- Implemented BT2 scenario 2022, $50/d.s.t.
- Focused on non-irrigated SWG ecotypes and MXG
- Select dominant species in the mix based on natural habitat and yield in the region
- Calculated yield and compared with ORNL and Biocro models – agreed well
- Estimated ET; compared estimates with measured ET from grass

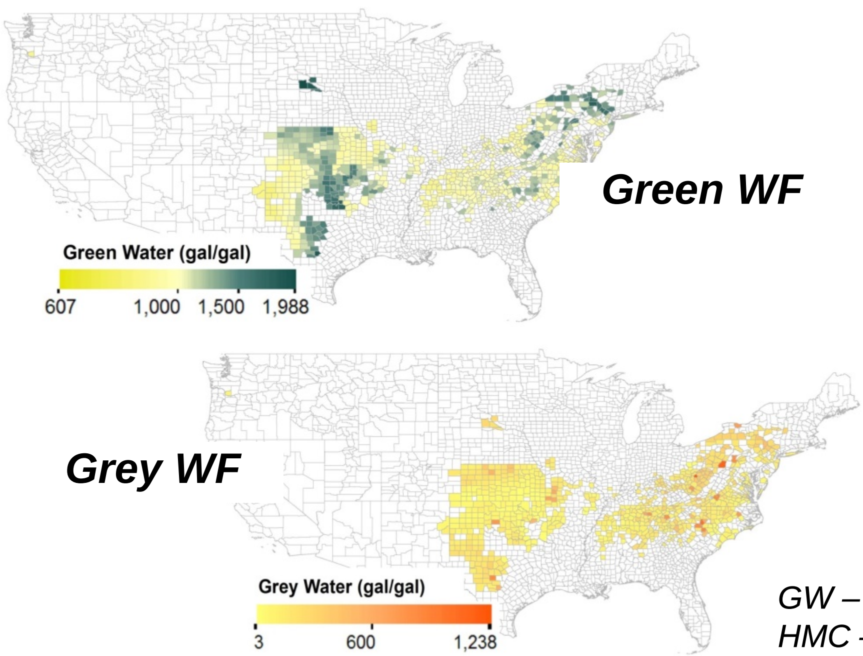
Distribution of Various Types



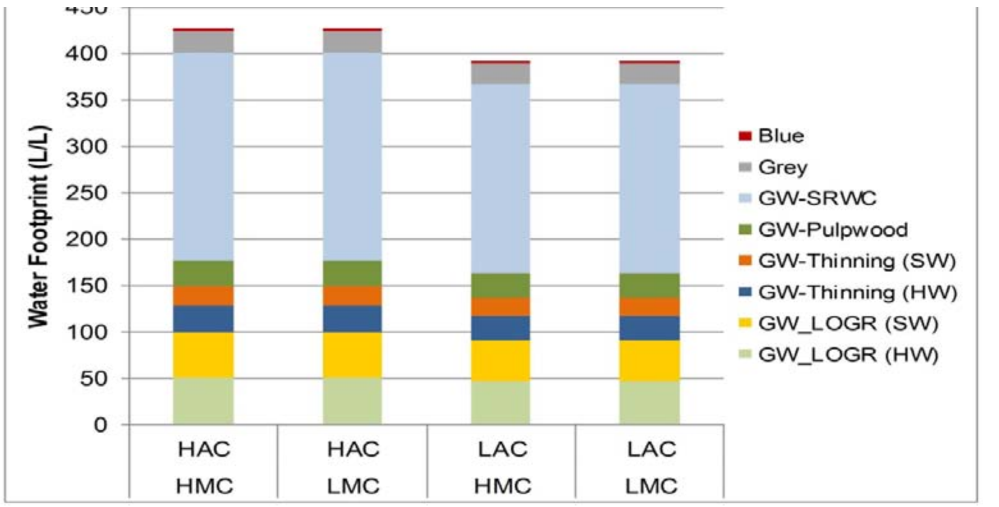


Analysis of Feedstock Mix Impact

Switchgrass, Miscanthus



WF of Forest Resources,
Advanced platform logistic design



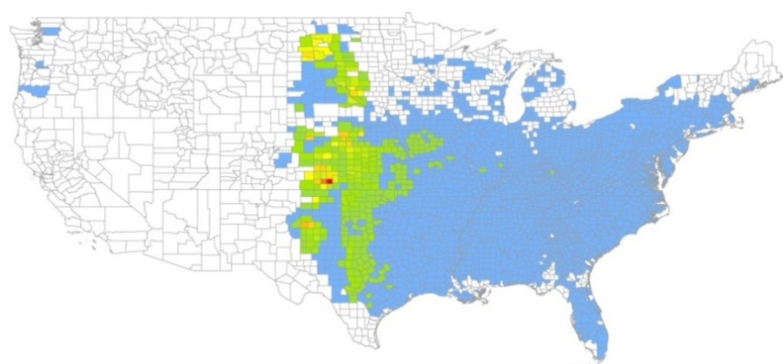
GW – green water HAC - high ash content LAC - low ash content
HMC – high moisture content LMC – low moisture content

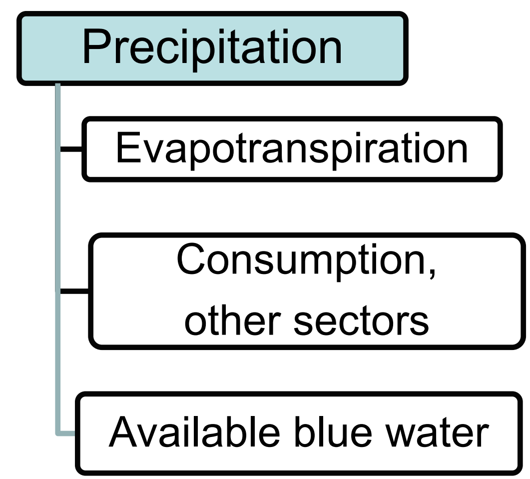
- Compared WF of perennial biofuel with other pathways
  - Low nitrogen grey water footprint
  - Aggregated intensity
- Estimated WF from forest feedstock mix (S.E.of U.S.)
  - Refinery sizing and logistic design scenario analyses (*Multi-lab collaboration*)
  - Hardwood, softwood, SRWC; selected counties
  - Feedstock mix is the determining factor for WF of mixed alcohol biofuel pathway

Evaluate of Water Resource Impact

- Analysis conducted to locate potential water-stressed areas associated with increased feedstock production
- Estimated annual blue water resource demand for biofuel produced from various feedstock under projected scenarios
  - Consider regional water demand from other sectors
  - Developed Blue Water Use Index
- Assessed using municipal wastewater as resource for algae:
  - Geographic mismatch between the wastewater source and potential pond location
  - Temporal variation of MWW affects water availability

Switchgrass and miscanthus





Blue Water Consumption in Energy Production
– Address Energy-Water Nexus

Liquid Fuel — drive a passenger car for a mile (regional average)

Corn ethanol:	0.7–10.4 gal	Midwest regions
Cellulosic ethanol:	0.1–0.3 gal	Non-irrigated perennial/wood residue
Petroleum gasoline:	0.1–0.3 gal	Onshore United States, Saudi Arabia, oil sand

Generate one million btu Electricity in Power Plant (gallons)

U.S. Average Mix	**164**
• Wind	0
• Geothermal	3 – 214
• Natural gas	6 – 202
• Biomass	12 – 179
• Nuclear	41– 249
• Solar	9 – 310
• Coal	18 – 439
• Hydroelectric	586

Sources:
Wu et al. 2009; Clark et al. 2011; Chiu and Wu, 2012; Wu et al. 2012

WATER (Water Assessment Tool for Energy Resources)

Launched May, 2013

An on-line interactive visual tool for water use, water resource, and water quality assessment

Features

- Multiple pathways; feedstock production and conversion stages
- Blue, green, and grey water footprint analysis
- United States, region, state, county

Production pathways

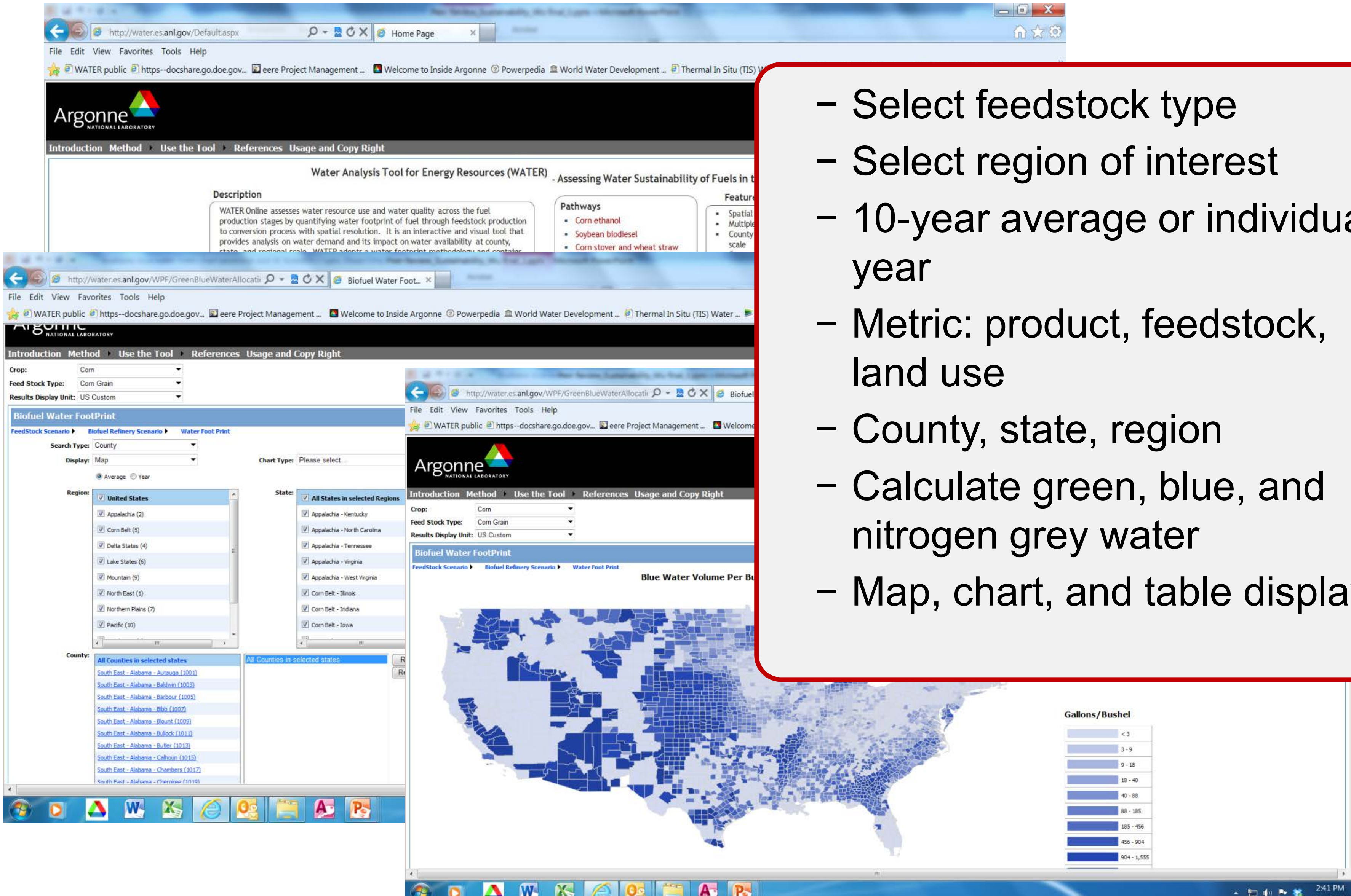
- Corn ethanol
- Soybean biodiesel
- Corn stover
- Wheat straw ethanol
- Perennial ethanol*
- Forest resource biofuel*

*** Under development**

- Build "what-if" scenario and generate region-specific results
- Support planning of sustainable development and deployment
  - Fuel facility site selection
  - Feedstock sourcing
- Serve fuel industry, feedstock producers, government, academia, general public

WATER

WATER.ES.ANL.GOV



- Select feedstock type
- Select region of interest
- 10-year average or individual year
- Metric: product, feedstock, land use
- County, state, region
- Calculate green, blue, and nitrogen grey water
- Map, chart, and table display

3 Relevance

- Provide consistent platform/method to examine water sustainability metrics for agricultural residue, energy crops, forest resources, and algae production pathways
  - WATER model translates feedstock / pathway selection into estimates of water resource demand and water quality impact.
  - SWAT modeling permits analysis of future water quality impacts of production scenarios and climate change
- Analyze water consumption in biofuel production stages
  - Identify regional specific low water intensity feedstock mix
  - Evaluate management programs/cropping systems that reduce nutrient and sediments loadings at watershed
- Support stakeholders
  - Robust, on-line, user-friendly tool with appropriate functionality
  - Facilitates decision makers to incorporate local water resource constraints in site selection for new projects, in addition to economic and infrastructure considerations.
  - Supports policy makers to compare and evaluate potential impacts of energy policies on natural resource

4 Critical Success Factors/Challenges

Success Factors

- Develop consistent methodology that provides detailed spatial analysis of water sustainability metrics
  - Feedstock specific methods have been developed in SWAT modeling and WF and applied to watershed or county scale
- Apply the method to examine the effect of management/practices and cropping systems associated with feedstock production to provide insights for landscape management, reducing negative impact and improving sustainability of the biofuel
- Collaboration

Challenges

- Data gap and quality
  - Broad collaboration for data collection and develop physical-based assumptions to fill the gap.
  - Data screening and comparison based on data year, location, crop type, collection method.
  - Uncertainty and sensitivity analysis.

5 Future Work

- Tool expansions and analysis
  - Implement cellulosic and advanced fuel pathways in WATER
  - Develop WF of additional hydrocarbon pathways
  - Continue to validate SRWC water use estimate by using additional field data (collaborators: Negri of ANL and Langholtz of ORNL)
- Watershed modeling
  - Analyze trade-offs among feedstock mix, fuel production, water consumption/use efficiency, and water quality at sub basin scale for MRB using SWAT model
  - Develop SWAT model for Lower Mississippi river basin (in collaboration with ORNL)

Summary

Approach

- Use spatial-explicit analytical framework to calculate water use, water resource and water quality impacts
- Key collaborator: Army Corp. Eng.

Technical Accomplishments

- WATER on-line tool
- County-level water footprint for perennials, algae, forest resource, agricultural residue, corn, soybean
- Webinars: Water foot print of biofuels
- SWAT models for UMRB, ORB, and MoRB; BT2 and climate scenarios
- Water sustainability indicators for UMRB and ORB

Relevance

- Provide consistent platform to analyze water quality and quantity impacts of cellulosic biofuel. Assist DOE stake holders with data acquisition / validation and analysis to estimate water resource impact of deployment of various biofuel feedstock mix and production pathways.

Critical Success factors

- Consistent methodology and application to multiple pathways

Technology Transfer and Future Work

- SWAT results to KDF; Publication
- WF of hydrocarbon pathways; WF tool
- Continue watershed modeling

Acknowledgement

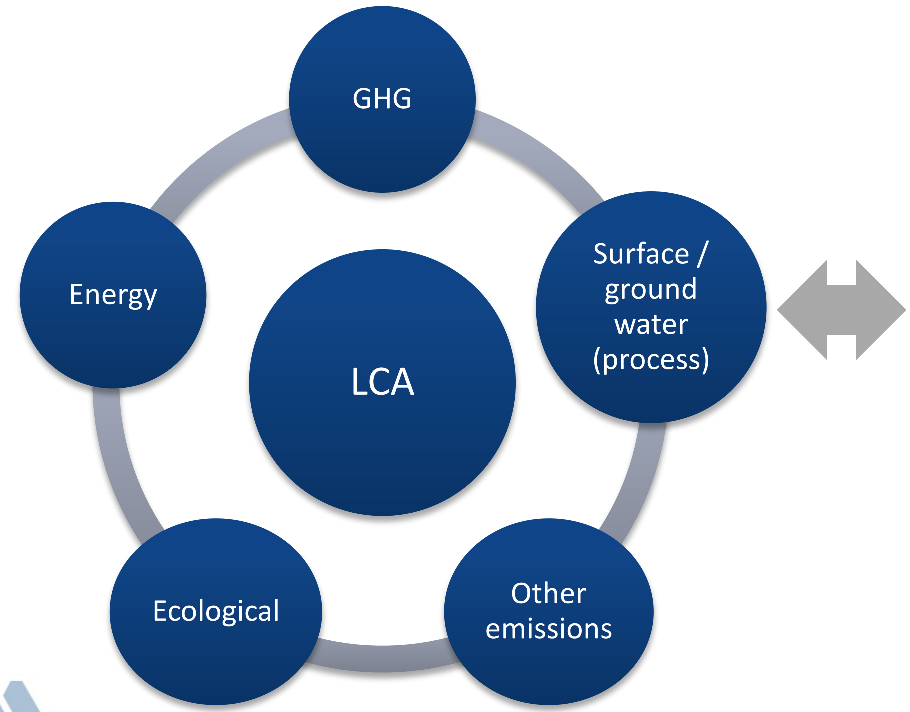
- BETO

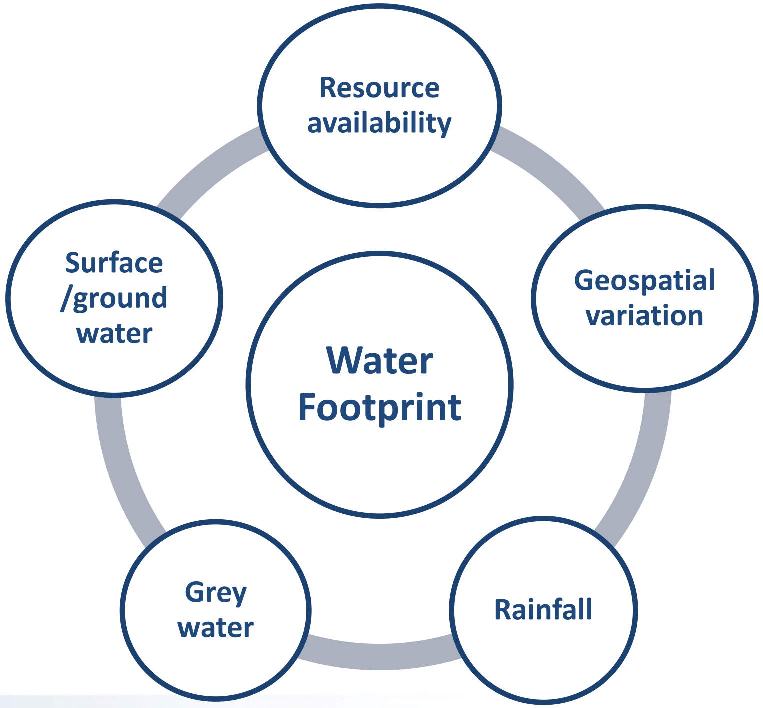
  Kristen Johnson, Alicia Lindauer, Alison Goss Eng, Zia Haq
- ANL: Michael Wang, Marianne Mintz, Salil Arora
- ORNL: Yetta Jager, Matt Langholtz, Laurence Eaton, Aaron Myers
- INL: Dave Muth, Jacob Jacobson
- NREL: Eric Tan, Abhijit Dutta
- PNNL: Lesley Snowden-Swan
- SI: Amy Schwab, Andrew Argo

Supplemental Water Resource Assessment to LCA

- Surface and ground water use in production process is both an input and an impact category in LCA.
- LCA presents average value in a region or country, while WF is spatial-resolution based.

Water footprint assessment supplements LCA by providing further analysis that links the surface and ground water consumption in process to geospatial distribution, feedstock requirement, and regional water resource availability, in addition to rainfall and grey water discharge.





Additional Slides

Responses to Previous Reviewers' Comments (2011)

1) Comparable analysis is needed

- We compiled additional results on blue water use for biofuel pathway (Mixcanthus, corn stover, and forest resources) from our study and compared them with petroleum oil and electricity generation.

2) Application of the SWAT model and WF analysis not addressed

- Detailed subbasin-scale SWAT analysis has been conducted to simulate watershed response to stover removal, change of rotation, LUC, and climate change at subbasin scale to identify weak spot in support of mitigation strategy development.
- WF of perennial grass and forest resource at county level
- Identified region-specific low-WF feedstock

3) Regional blue water resource availability assessment should be addressed

- We have conducted water availability analysis for corn-, soybean-, perennial-, forest resource-, and algae-derived biofuel pathways; determined blue water use index.

Publications and Presentations

- Zhang, ZL, M. Wu. 2013. Evaluating the Transport and Fate of Nutrients in Large Scale River Basins Using an Integrated Modeling System, in Landscape Ecology for Sustainable Environment and Culture, Ed. Bojie Fu, K. Bruce Jones, Springer.
- Chiu, Y. and M. Wu, Water footprint of biofuel produced from forest wood residue via a mixed alcohol gasification process, under review with ERL.
- Argo, A. E. Tan, D. Inman, M. H. Langholtz, L. M. Eaton, J. J. Jacobson, C. T. Wright, D. J. Muth Jr, M. Wu, Y. Chiu, R. L. Graham. Investigation of biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system and advanced uniform biomass logistics designs, Biofuels, Bioprod. Bioref. (2013) DOI: 10.1002/bbb.1391.
- Chiu, Y., M. Wu. Considering water availability and wastewater resources in the development of algal bio-oil, Biofuels, Bioprod. Bioref. (2013) DOI: 10.1002/bbb.1397.
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- Wu, M., Chiu, Y., and Demissie, Y., Quantifying the Regional Water Footprint of Biofuel Using Multiple Analytical Tools, Water Resource Research. (2012) VOL. 48, W10518,.
- Wu, M., Demissie, Y., Yan, E. Assessing the Impact of Future Biofuel Scenario on Water Quality and Water Cycle Dynamics, Biomass & Bioenergy, 41(2012)44-56.
- Wu, M. and M. J. Peng, Developing a Tool to Estimate Water Use in Electric Power Generation in the United States, ANL/ESD/11-2, Dec. 2010. Updated July 2011.
- Wu, M., M. Mintz, M. Wang, S. Arora, Y. Chiu. "Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline – 2011 Update", ANL/ESD/09-1 – Update, Energy System Division, Argonne National Laboratory, Argonne, IL. Aug. 2011.
- Wu, M., M. Mintz, M. Wang, S. Arora, Water Consumption in the Production of Ethanol and Petroleum Gasoline, Environmental Management, (2009) Vol. 44, pp981–997
- Gopalakrishnan, G., M. Negri, M. Wang, M. Wu, S. Snyder, and L. Lafreniere, Biofuels, Land, and Water: A Systems Approach to Sustainability, Environ. Sci. Technol. (2009) 43, 6094–6100

Selected presentations and webinars:

- IIT, 2013, GAO 2012, EST 2012, AWRA 2012, EBI, 2012, AGU 2010-2012, GWPC 2009-2010, BIOMASS 2010-2011, Purdue Symposium on Water/Agriculture/Climate Change, 2010, ORNL Watershed workshop 2010, ACS National Meeting 2009, ACLCA IX Conference 2009
- DOE BETO, 2012; Water Usage Webinar by The Horinko Group, 2012, DOE Clean Cities, 2012.