Oak Ridge National Laboratory

DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

4.2.2.41 Short-rotation woody biomass sustainability

March 4-8, 2019
Analysis and Sustainability

Natalie A. Griffiths
Oak Ridge National Laboratory

C. Rhett Jackson
University of Georgia

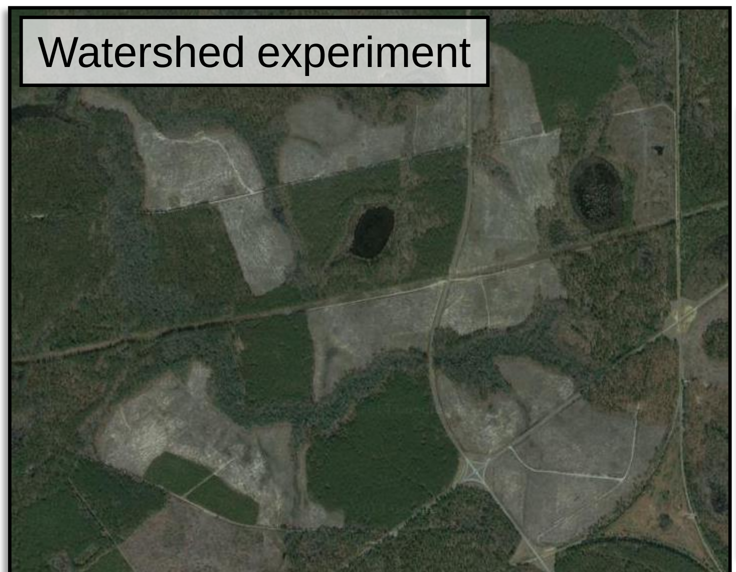
ORNL is managed by UT-Battelle, LLC
for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

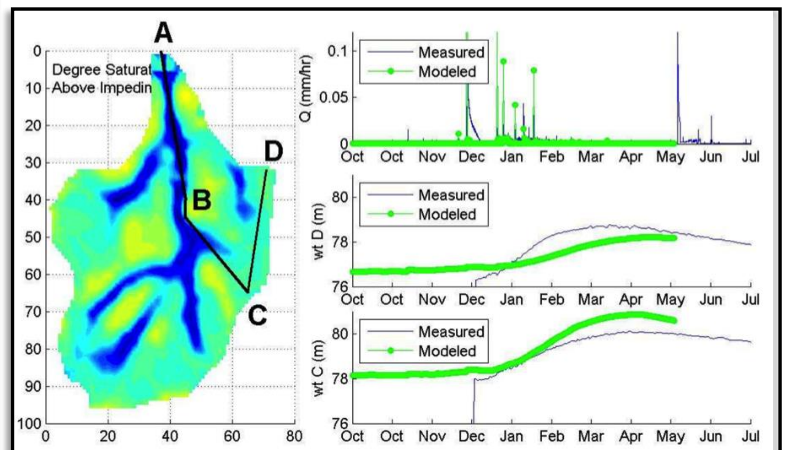
Goal Statement

- Use a watershed-scale experiment and a distributed watershed modeling approach to evaluate the environmental sustainability (water, soil, and productivity indicators) of intensive short-rotation woody crop (SRWC; loblolly pine) management for bioenergy in the southeastern US.

- Determine whether current forestry Best Management Practices (BMPs) are adequate to protect water and soil resources.



Watershed models



- **Relevance:** project will measure and model key sustainability indicators in an operational-scale SRWC experiment and provide information to industry, state water quality foresters, and regulators on the efficacy of current forestry BMPs for SRWC production for bioenergy.

Quad Chart Overview

Timeline

- Original project start date: FY10
- Merit review cycle start date: FY18
- Project end date: FY18
- Percent complete: 90%

Objective

- Evaluate the environmental sustainability of intensive SRWC production for bioenergy in the southeastern US using field experimental and watershed modeling approaches.

End of Project Goal

- Validate environmental sustainability of SRWC production technology and provide a baseline relative to current BMP studies.

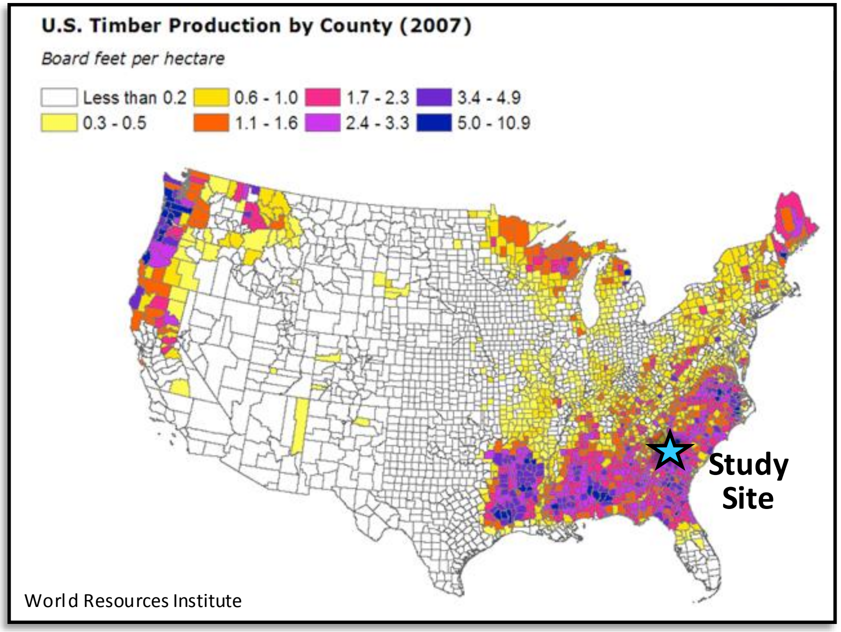
Barriers addressed

- At-C: Data availability across the bioenergy supply chain.
- At-E: Quantification of economic, environmental, and other benefits and costs.

	Total Costs Pre FY17	FY17 Costs	FY18 Costs	Total Planned Funding (FY19 onward)
DOE BETO Funded:				
ORNL	2294K	345K	345K	0K
University/ USFS-SR	3186K	310K	310K	0K
Collaborator Cost Share:				
Universities	978K	81K	107K	0K
USFS	710K	76K	10K	0K

1 - Project Overview

- Southeastern US projected to be an important source of SRWCs for bioenergy production.
- Loblolly pine has been identified as the top candidate feedstock for bioenergy in the southeast (Kline and Coleman 2010).



- Water and soil impacts of intensive SRWC production have not been evaluated at the watershed scale (Griffiths et al. 2018). Major difference between SRWC and pulp/sawtimber systems is greater weed control and fertilization prior to crown closure and more frequent ground disturbance in the short-rotation system.
- Current forestry BMPs not tested for SRWC production, including SRWCs with accelerated growth due to complete weed control and frequent fertilization.

Oak Ridge National Laboratory

1 - Project Overview

Project History and Goals:

- Project initiated in 2009 at watersheds set aside at the Savannah River Site (SRS) for environmental R&D of intensive biomass.
- Assess effects of intensive SRWC production on water and soil indicators relative to regulatory and narrative standards for forestry.
- Evaluate hydrologic effects of SRWCs at larger spatial and temporal scales using a distributed watershed modeling approach.
- Evaluate effectiveness of current forestry BMPs for SRWC production.

OAK RIDGE National Laboratory

2 - Approach (Management)

Division of tasks based on scientific expertise:

Water quality	Hydrology	Water use	Modeling	Soil quality	Forestry
Oak Ridge National Laboratory	University of Georgia; University of Saskatchewan	The University of Alabama	Oregon State University OSU; University of Georgia	Forest Service U.S. Department of Agriculture; University of Georgia	Forest Service U.S. Department of Agriculture

Collaborative project requires frequent team meetings, on-site researchers, and communication with BETO:

- Monthly conference calls.
- Bi-annual project meetings.
- On-site, full-time field technician.
- Research scientists based at SRS.
- Quarterly reporting and update calls with BETO technology manager.
- Milestones divided by tasks to monitor progress.

2 - Approach (Technical)

Coupled Experimental-Modeling Approach:

- Before-after control-intervention operational-scale watershed experiment.
- Intensive practices are state-of-the-art:
  - Sub-soiling, multiple herbicide and fertilizer applications, advanced genetic material.
- Evaluating effectiveness of South Carolina forestry BMPs.
- Process-level field observations used to develop a watershed model specific to the Upper Coastal Plain.
- Modeling will upscale results spatially and temporally. Modeling scenarios developed with input from stakeholders and industry.

2 - Approach (Technical)

Success Factors:

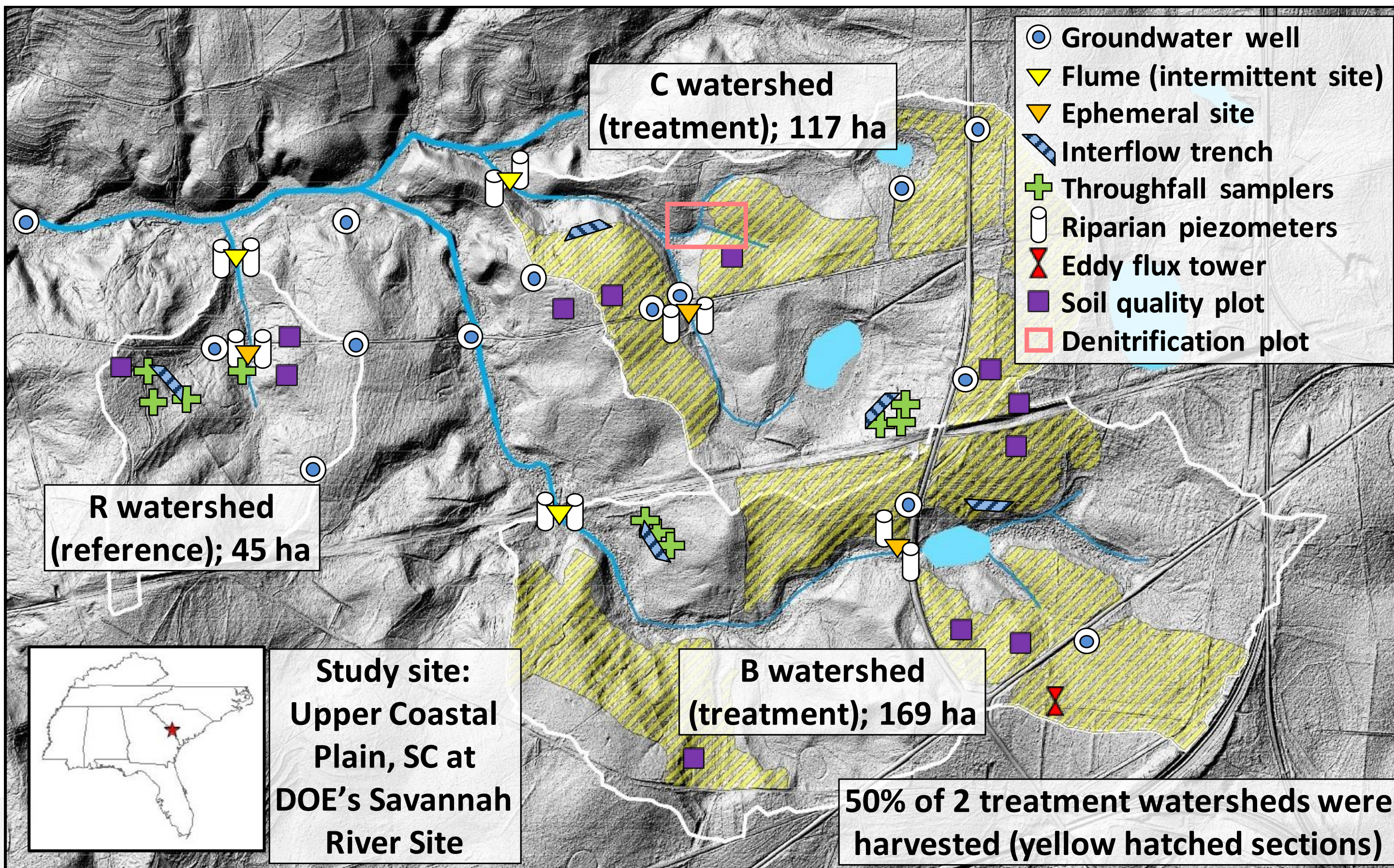
- Rapidly addressing field issues (e.g., instrument failures, storms).
- Collecting high-quality data.
- Scaling field results using models.
- Disseminating findings to relevant audiences, including publishing data on the BioenergyKDF and results in peer-reviewed journals.
- Engaging industry (NCASI) and state water quality foresters on forest management modeling scenarios.

Challenges:

- Experimental design (i.e., droughts/floods, pests, storms).
- Measurements (i.e., groundwater transit times, instrument failures, analytical backlogs, eddy flux calculations with rapidly growing trees).
- Modeling (i.e., including climate change scenarios, flexibility of standard model frameworks for simulating dynamic landscapes over time).

3 - Accomplishments: Expt. Treatments

- 3 highly instrumented forested watersheds: 1 reference and 2 treatment.
- **Site characteristics:** low-relief topography, poor-to-moderate quality sandy soils overlaying clay. Organic-rich riparian zones, intermittent and ephemeral channels. Watersheds typical of the Upper Coastal Plain.



3 - Accomplishments: Silviculture

Pre-treatment (2010-2012) — **Post-treatment (2012-2018)**

2010 — 2012 — 2014 — 2016 — 2018*

*1/2 way through rotation

Harvest: 40% of treatment watersheds, 20 Mg/ha residues for bioenergy

Site prep: ripping/sub-soiling

Herbicide: imazapyr and glyphosate

Planting: loblolly pine seedlings at 545/acre (AGM MCP 37 growth is 70% > than SE reference)

Herbicide: sulfometuron methyl and imazapyr

Fertilizer: DAP

Herbicide: sulfometuron methyl
Pesticide: fipronil
Fertilizer: urea

Fertilizer: DAP/urea
Herbicide: sulfometuron methyl

Fertilizer: urea (aerial application)

3 - Accomplishments: Hydrology

Objectives:

- Characterize dominant hydrologic processes.
- Collect time series hydrologic data to inform and test hydrologic models.

Results:

- Multiple lines of evidence demonstrate that groundwater is the dominant hydrologic pathway (Jackson et al. 2014, 2016, Du et al. 2016). Stream water is isotopically and chemically distinct from hillslope water (Klaus et al. 2015, Griffiths et al. 2016). **The most likely stream water quality effects will be via a groundwater pathway.**
- Theoretical analysis and travel time modeling indicate that interflow over the subsurface clay layer can effectively transport N only from the lower reaches of hillslopes (Jackson et al. 2014, Klaus and Jackson 2018). This was a general result, applying well beyond our site to all but the steepest hillslopes on unweathered crystalline rock.

All milestones completed: 6 papers published on hydrologic and biogeochemical flow paths.

3 - Accomplishments: Carbon/Water Flux

Objective: Determine how stand development and climatic variation affects the carbon and water dynamics of an intensively managed bioenergy crop.

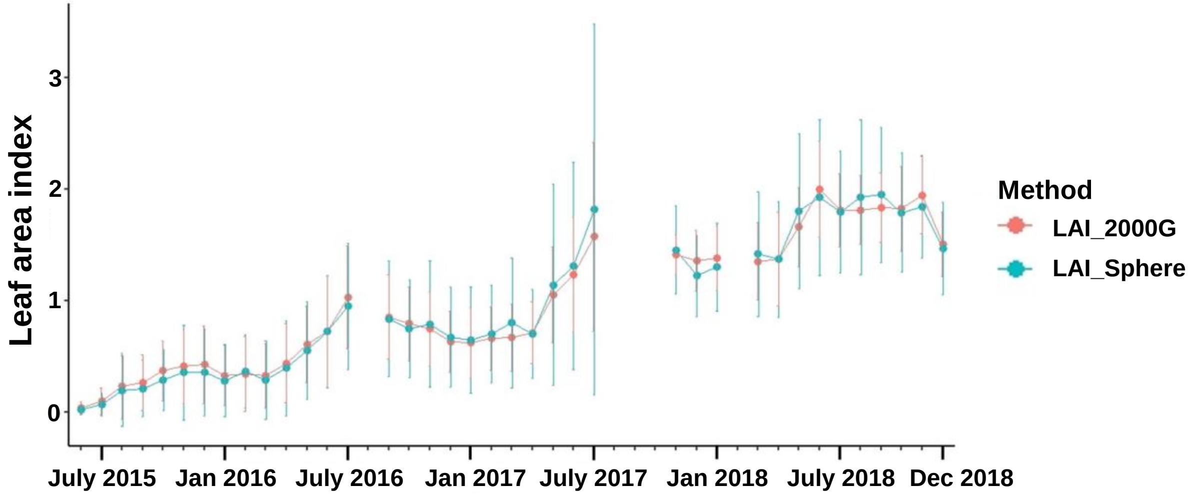
Results:

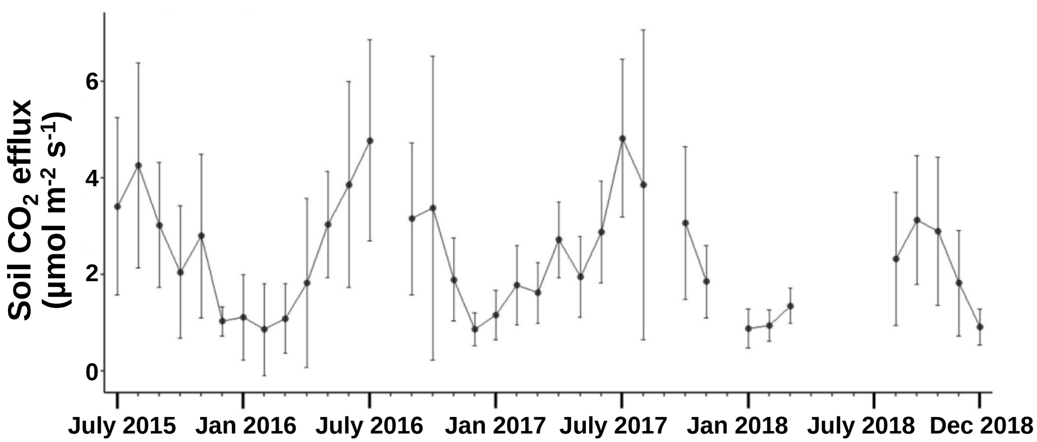
- ~4 y of eddy covariance data collected.
- C fluxes suggest that pine is ~6 to 14 y ahead in C sequestration capacity compared to standard timber plantations.
- ET rates comparable to 10 to 20-y-old loblolly pine stand in NC (Sun et al. 2010).
- Bowen ratios remain lower than traditional timber plantations.

State	Location	Age	Year	WUE (g C/mm)	LAI	-NEE (g C/m²/y)	-GEE (g C/m²/y)	R_{eco} (g C/m²/y)	ET (mm)	B	References
SC	**Bioenergy Plantation**	**3-6**	**2018**	**5.70**	**0.03-1.41**	**161-771**	**2287-3091**	**2126-2625**	**540-901**	**0.53±0.02**	**Current**
NC	Conventional plantation	4-6	2005-2007	NA	NA	NA	NA	NA	755-885	1.45±1.2	Sun et al. 2010
NC	Conventional plantation	13-15	2005-2007	NA	2.4-4.4	361-835	2482-2491	2051-2121	1011-1226	0.89±0.7	Noormets et al. 2010; Sun et al. 2010
NC	Conventional plantation	20-22	2003-2005	3.26-3.77	NA	173-712	1954-2184	1665-2136	579.5-599.7	NA	Tian et al. 2010; Novick et al. 2015
NC	Intercropped Pine/Switchgrass	2-4	2010-2012	3.8-4.5	0.3-1.9	NA	1136-1903	NA	453-580	NA	Albaugh et al. 2014

3 - Accomplishments: Carbon/Water Flux

- Leaf area is continuing to expand rapidly. Canopy closure expected by end of 2019 growing season; ~2-3 y ahead of conventional timber plantations.
- Also expected that high rates of stand physiological activity would lead to rapid increases in soil respiration which has not been seen to date.





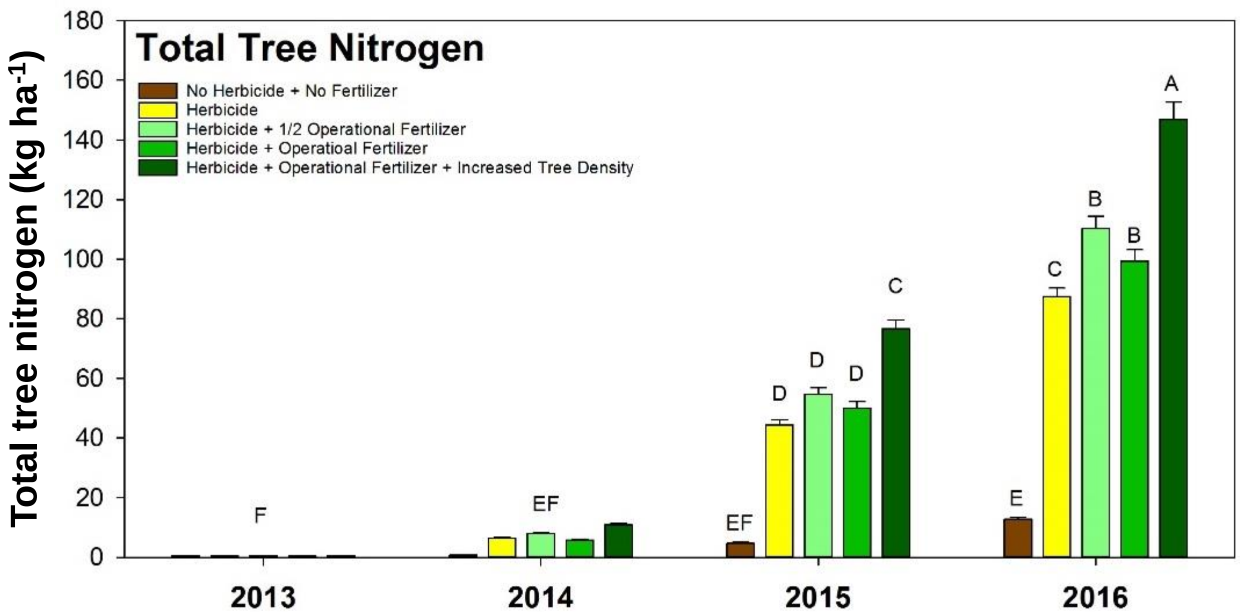
All milestones completed: 3 years of C flux and ET data analyzed. Fourth year analysis will be completed in early 2019. One paper on C fluxes in review.

3 - Accomplishments: Ecosystem N Budget

Objective: Measure soil quality and productivity responses to varying levels of fertilizer & herbicide at the plot scale.

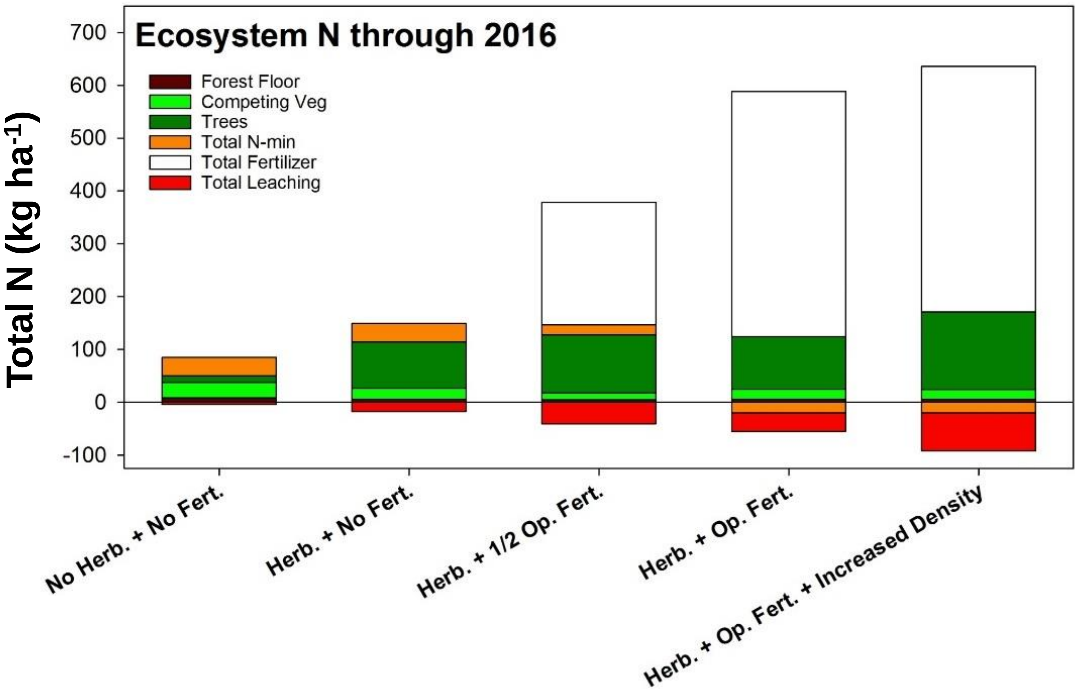
Results:

- N-uptake by pine was low through 2014, and lower than competing veg. Pine N uptake increased in 2015-2016.
- Pine N-uptake could have been satisfied by N-mineralization in 2013-2014. Control of competing vegetation could free up N.
- **Herbicide application important for increasing aboveground biomass.**



3 - Accomplishments: Ecosystem N Budget

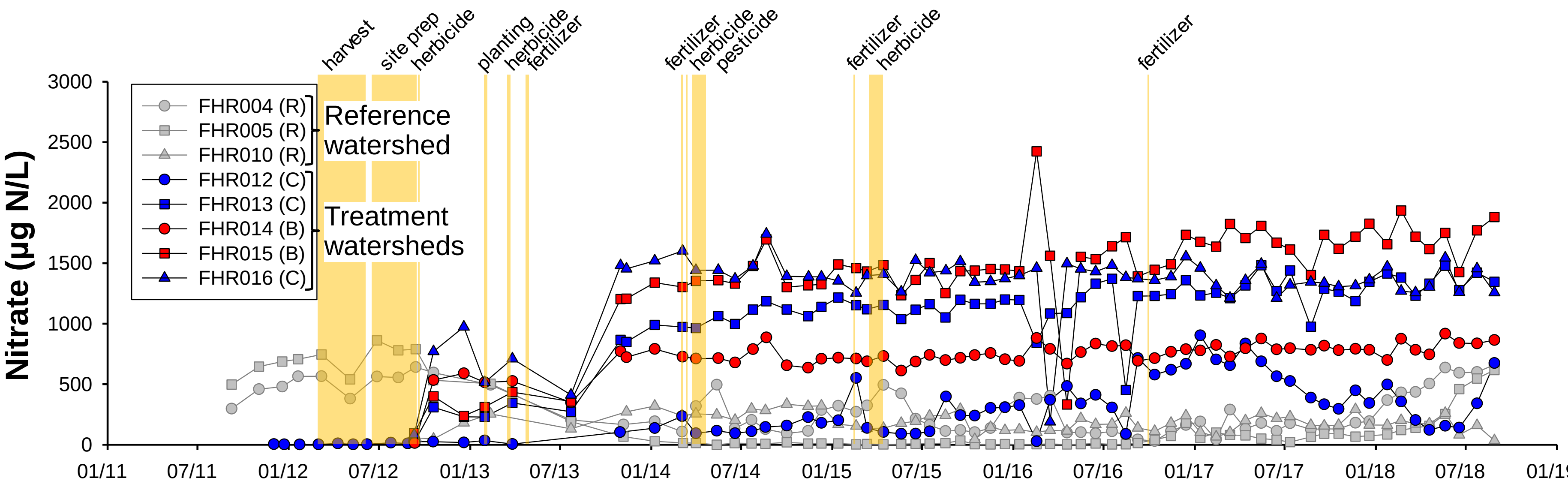
- Nitrate leaching was high in 2013, decreased in 2015-2016.
- Through 4 growing seasons ½ op. fert. appear to satisfy pine N demand and minimize leaching. Higher density planting increased productivity.
- Op. silvicultural treatment resulted in ~30% of applied N taken up by trees and higher nitrate leaching.
- **Some aspects of the silvicultural treatments were efficient (early competition control) and some aspects were not (early fertilization).**



All milestones completed: Analysis of 2016 growing season complete. Field sampling for 2017 growing season complete. Laboratory analyses of 2017 samples in progress.

3 - Accomplishments: Water Quality

Objective: Examine the short- and long-term effects of short-rotation pine production on water quality.

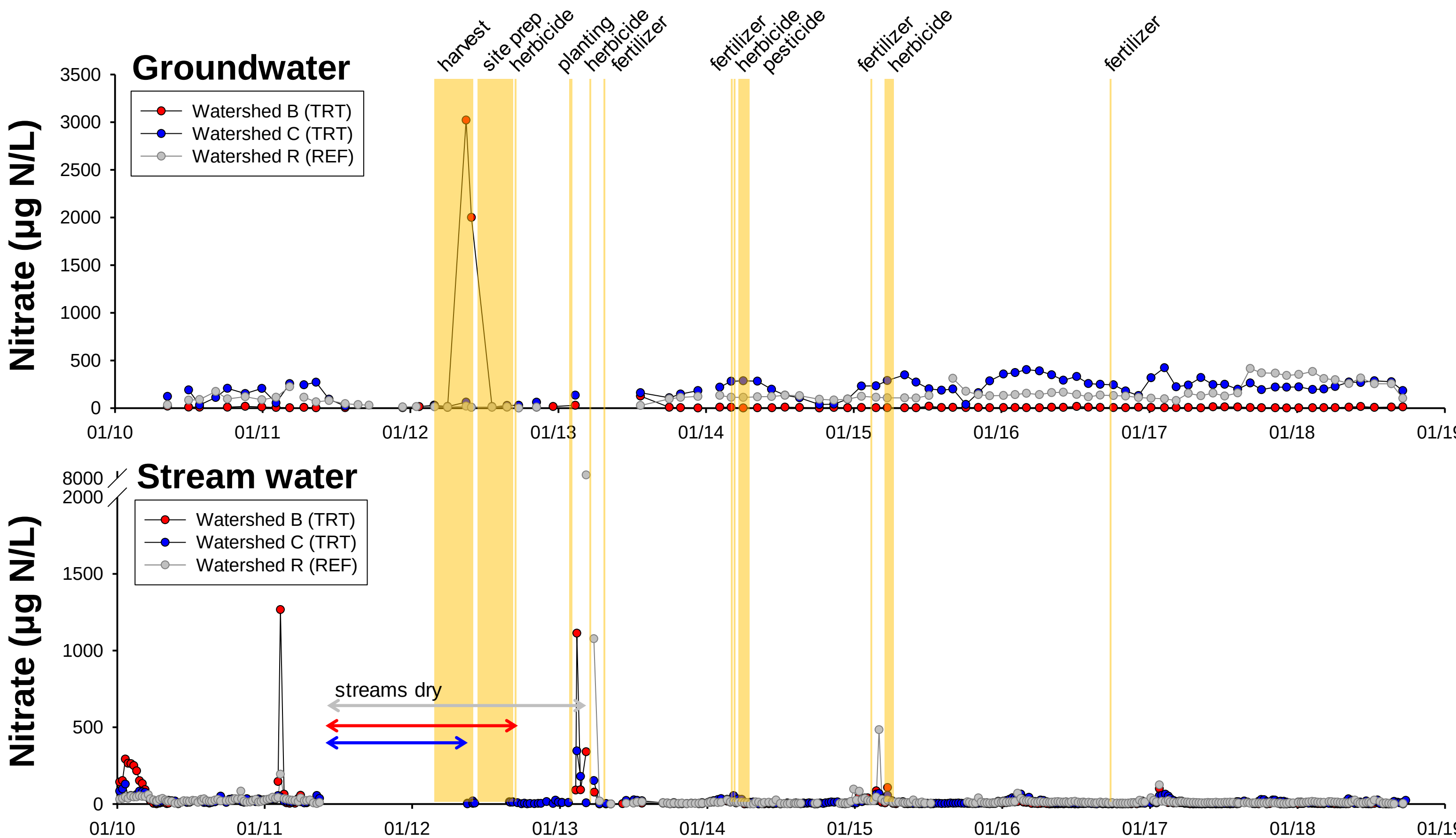


Results:

- [Nitrate] elevated in groundwater after harvest and first fertilizer application. Concentrations <2 mg N/L (drinking water limit = 10 mg N/L).
- No changes in ammonium, soluble reactive phosphorus (SRP) concentrations. Herbicides and pesticides below detection.
- **Nutrient uptake is inefficient resulting in nitrate leaching to groundwater.**

3 - Accomplishments: Water Quality

- Elevated nitrate in groundwater has not yet reached the riparian areas/ stream or has been taken up/transformed.
- **BMPs appear to protect surface water quality.**



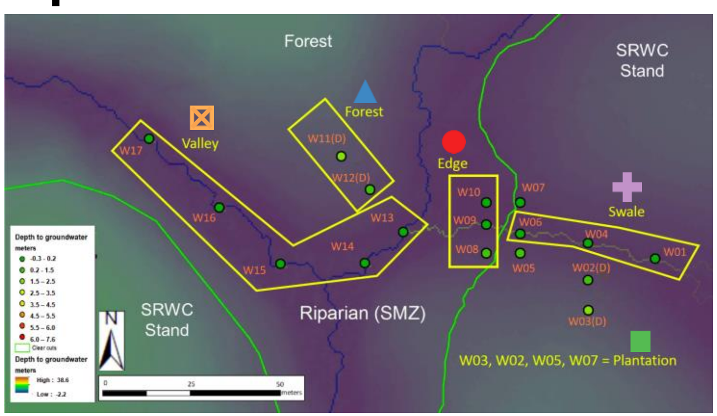
All milestones completed: NH_4, NO_3, SRP analyses complete. Water quality manuscript published (Griffiths et al. 2017).

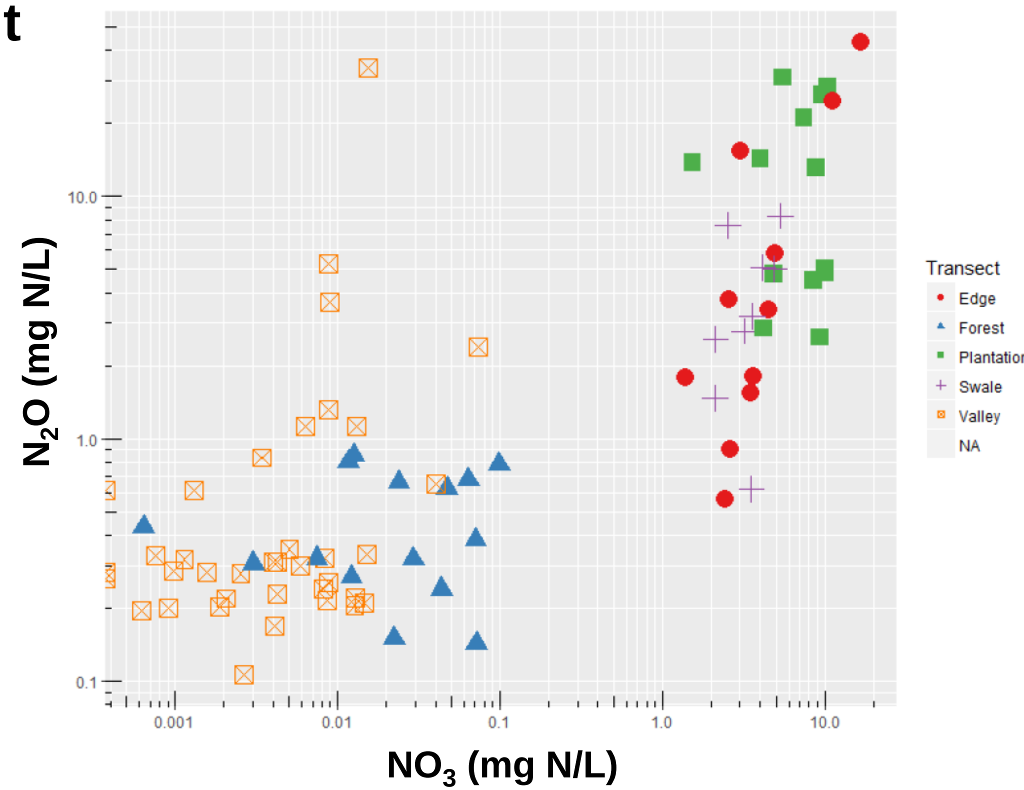
3 - Accomplishments: Denitrification

Objective: Quantify denitrification along a shallow groundwater flow path.

Results:

- Rapid biogeochemical transformation and denitrification in forested wetland valleys.
- Net denitrification reducing >80% of N in the shallow groundwater system within the valley of the SMZ. Upland locations reducing 47-60%.
- **Denitrification likely important in removing elevated nitrate from these watersheds, especially in organic-rich riparian zones/SMZs.**

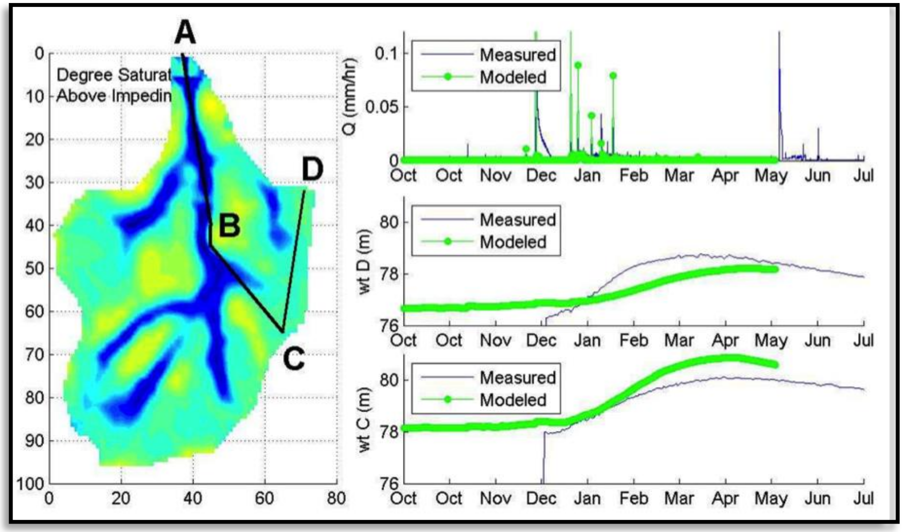




3 - Accomplishments: Hydrologic Modeling

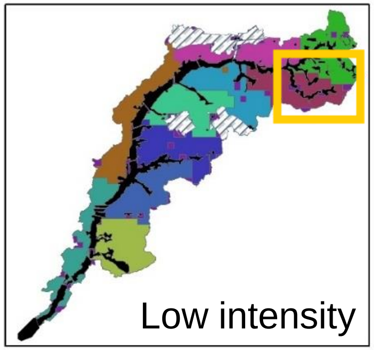
Objectives:

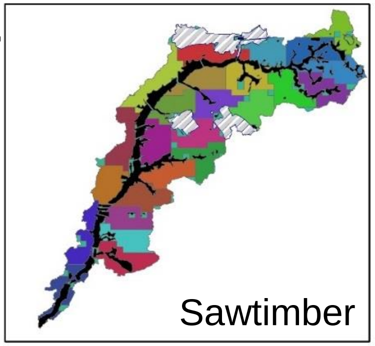
- Develop a watershed model (Envision) using functional relationships between vegetation cover, meteorological variables, soil moisture, and groundwater dynamics.
- Use model to evaluate potential impacts of various forest management scenarios across the SRS site. Models developed with input from foresters and industry.
- Evaluate influence of SRWC production on hydrology at local and regional scales, including results from 3 different models; Envision, MIKESHE, and SWAT.

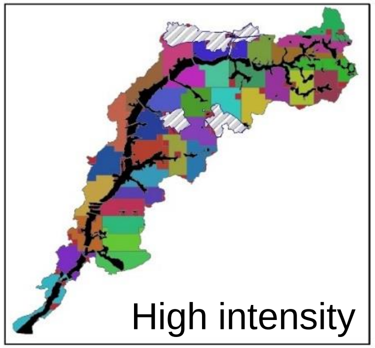


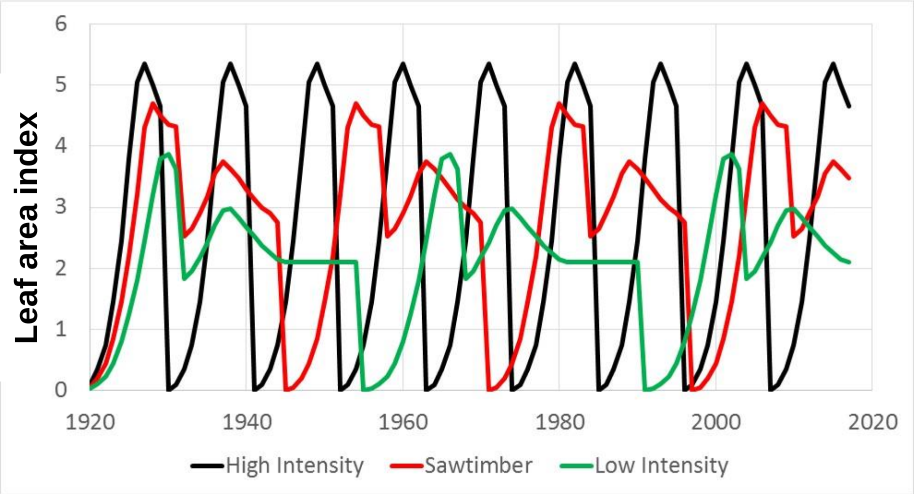
3 - Accomplishments: Hydrologic Modeling

- Three models used to evaluate impacts of SRWC scenarios on long-term hydrological response in Fourmile watershed.
- Four possible forest management scenarios were developed:
  - Baseline (minimally managed forest based on vegetation condition in R watershed).
  - Low-intensity forest management (35 yr rotation).
  - Sawtimber/pulp management (25 yr rotation, 12 yr thinning).
  - High-intensity woody biomass production (10 yr rotation).
  - High-intensity woody biomass production with 50% land in agriculture.



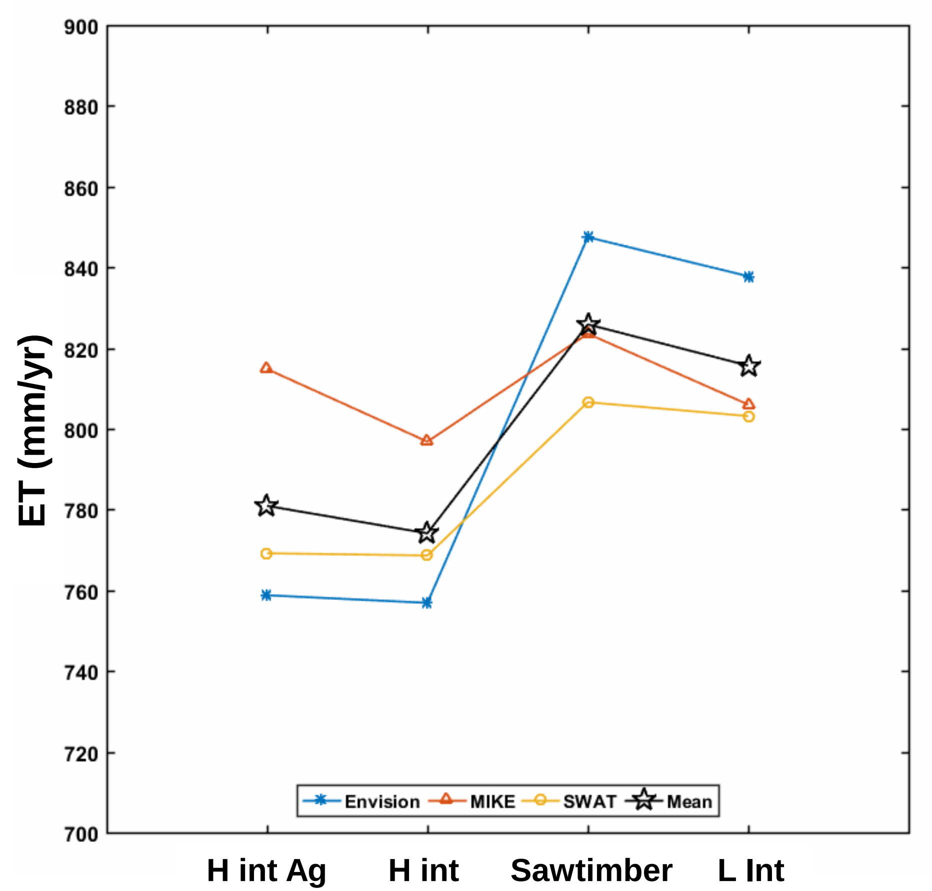






3 - Accomplishments: Hydrologic Modeling

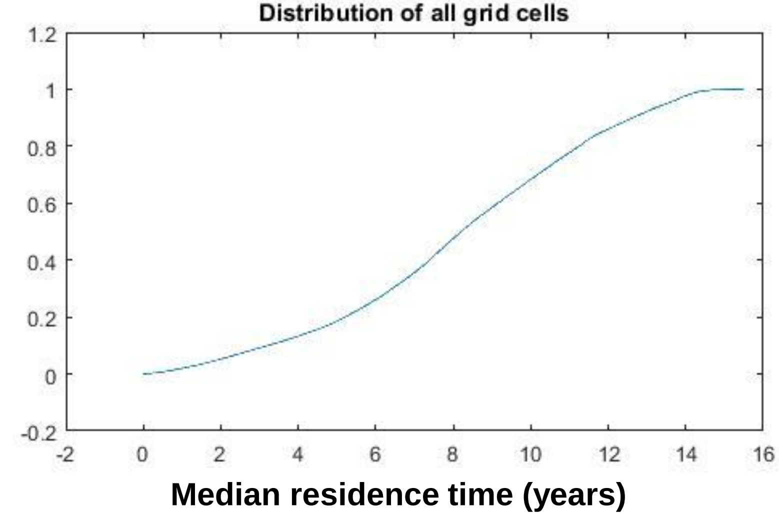
- Three models used to evaluate impacts of SRWC scenarios on long-term hydrological response in Fourmile watershed.
- Larger scenario differences (up to 100 mm/yr) for evapotranspiration (ET) than for discharge.
- Suggests ET is the primary variable influenced by forest landcover.
  - Larger/older trees result in increased ET values.
- Ensemble Mean (☆) suggests decreased ET for high intensity operations.
- Structural differences in models cause deviations in some predictions.

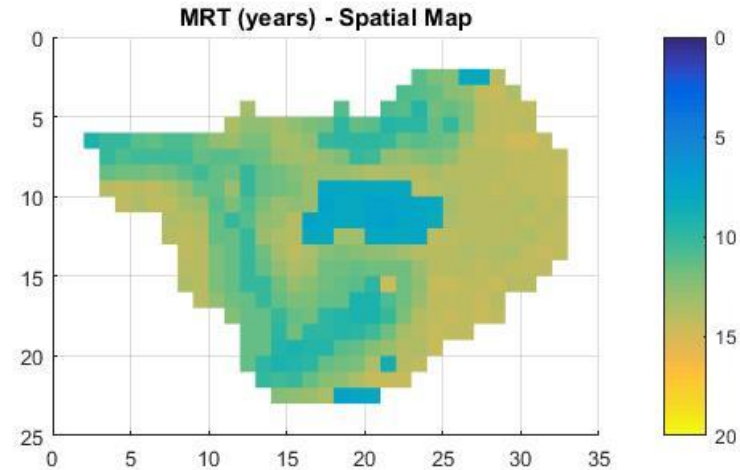


OAK RIDGE National Laboratory

3 - Accomplishments: Hydrologic Modeling

- Tracer simulations used to estimate spatial distribution of residence time in experimental watersheds.
- Results are included in an early draft manuscript completed during the 4th quarter FY18.
- Groundwater residence time varies in space, from <1 year to ~15 years.
- Median groundwater residence time is around 8 years.
- Suggests that elevated nitrate in groundwater may have reached some stream areas. Further suggests the importance of biological processes in removing nitrate before reaching the stream.





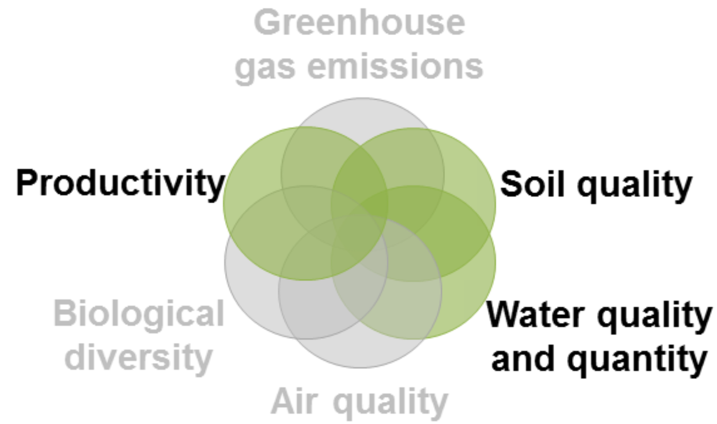
All milestones completed:
All modeling analyses completed. Three manuscripts in prep.

3 - Accomplishments: Dissemination of Results

- **Last 2 years:** 5 publications, 17 presentations.
- **Project duration:** 12 publications (plus 2 in review, >10 in prep.), 62 presentations, 9 theses in progress/completed, 7 post-docs.
  - Presentations at relevant meetings:
    - Society of American Foresters National Convention.
    - Symposium on Forestry BMP Effectiveness.
    - Short Rotation Woody Crops Operations Working Group Conference.
    - National Bioenergy Day Webinar.
    - Symposium on Watershed Scale Sustainability of Forest-Based Bioenergy Production.
    - NCASI Southern Regional Meeting.
    - Southern Group of State Foresters 2013 Meeting.
- Review paper on environmental effects of SRWCs published in GCB Bioenergy (Griffiths et al. 2018).
- Completed draft of final project report, focused on BMP effectiveness. Will be published as an ORNL Technical Report in 2019 and shared via the BioenergyKDF.

4 - Relevance

- Maintaining or improving environmental conditions under bioenergy feedstock production is a key goal of BETO. Protection of water and soils is critical.
- Measuring key sustainability indicators in an operational-scale SRWC experiment.
- Compared outcomes to regulatory and narrative standards for traditional forestry.



- Demonstrated that current forestry BMPs are adequate to protect water and soils. Publications, reports, data, and presentations to inform industry, state water quality foresters, and regulators.
- Upscaled and generalized results both spatially and temporally using a distributed hydrologic model.
- Advancing scientific understanding of watershed hydrology and biogeochemistry in Coastal Plains.

5 - Future Work

- Wrap up field and laboratory analyses.
- All team members will continue working on multiple planned publications.
- Data will be made available via the BioenergyKDF after publication.
- Finalize report summarizing project findings, focused on BMP efficacy. Will be released to the BioenergyKDF in 2019 (ORNL TM 2018-1055).

Summary

1. Overview:
   - Data are needed to evaluate the effects of SRWCs for bioenergy on water and soils in the southeast US and effectiveness of current forestry BMPs.
   - Findings will be used by state water quality foresters and industry to minimize environmental effects when implementing this SRWC technology in the southeastern US.
2. Approach:
   - Coupled watershed-scale experimental and modeling approaches to assess effects of SRWCs at various spatial and temporal scales.
   - Success depended on implementing treatments, collecting high-quality data, scaling results using models, disseminating results to relevant audiences.

Summary

3. Technical Accomplishments:
   - Pine growth was accelerated, and C sequestration rates were high in the first four years. Early herbicide efficient, early N fertilization not as efficient.
   - Quick flow paths rarely important in delivering solutes and sediments to the streams. Excess fertilizers may enter streams mainly via groundwater.
   - Nitrate leaching was high initially and nitrate increased in groundwater.
   - No increases in stream water nitrate. BMPs appear effective at maintaining stream water quality through the first few years, likely because an intact riparian zone allows for vegetative uptake and denitrification to remove nitrate from the ecosystem.
   - Modeling suggests some changes to the hydrologic cycle with SRWC production but structural differences in models cause deviations in some predictions.

Summary

4. Relevance:
   - Woody biomass grown in the southeastern US may be a dominant bioenergy feedstock.
   - Critical to evaluate whether current forestry BMPs are adequate to protect water and soils or whether bioenergy-specific BMPs are necessary.
   - Project directly measures key sustainability indicators and aligns with BETO's MYP goals.

5. Future Work:
   - Wrap up field and laboratory analyses.
   - Work on multiple publications.
   - Disseminate data and final project report via the BioenergyKDF.

Additional Slides

Responses to Previous Reviewers

Reviewer comment: *It would be useful to provide a little more background as to why the particular region was chosen, the particular silviculture approach, and also what initial hypotheses were regarding the BMP, notably the effect of fertilization.*

Response: Regarding the chosen region, the southeast is the dominant US wood production region due to a climate that is favorable for rapid tree growth and that 90% of forest lands are privately owned. Within the southeast, loblolly pine accounts for the vast majority of wood production. Widespread technical and human infrastructure exists for the growth, harvest, transport, and processing of loblolly pine. The region has made tremendous advances in the genetics of loblolly pine, including breeding and propagation. The major silviculture systems are established and it is known that weed control and nutrition are critical to achieve rapid early growth. Loblolly pine was also identified by southeastern foresters as the top candidate feedstock for bioenergy production (Kline and Coleman 2010). Thus, loblolly pine is the single species most likely to contribute to woody bioenergy feedstocks in the southeast. In addition, pines are usually grown on lands that are marginal for crop growth and thus avoid conflicts with agricultural production.

In terms of the silvicultural approach, small plot studies in the region have shown that maximum production in loblolly pine is achieved by complete weed control and annual fertilization. We attempted to mimic those studies operationally by applying several treatments of herbicide and by fertilizing initially and subsequently each year at low levels until crown closure. We chose to push the system in terms of early fertilization and weed control beyond current practice to not only accelerate growth, but also to enable us to address the potential impacts relative to current BMPs that were not developed in reference to SRWCs with accelerated growth. Regarding hypothesized effects, it is well known that the period following harvesting and new stand development is the most significant period for water quality impacts. This is due to more bare soil being exposed, potentially leading to increased erosion and transport of sediment and nutrients to streams. Further, limited vegetation growth can reduce water and nutrient uptake, leading to increased leaching of nutrients. Thus, we hypothesized that water quality effects may be observed in the first few years after harvest and establishment of loblolly pine.

Regarding BMPs and relevance to SRWCs, BMPs for forest harvest and planting have been implemented, tested, and refined since the late 1970s. BMPs vary across states, but all include riparian buffers, minimization of bare soils, separation of roads and landings from streams, dispersal of road and landing runoff, and minimization of stream crossings. Current BMPs are predicated upon standard silvicultural techniques and rotations (18 years for pulp and 25-35 years for sawtimber). Economic calculations for such silviculture assume that tops and limbs will not be commercially valuable and will be left on site. In a biomass market, however, the whole tree becomes valuable, and a shorter rotation (10-12 years) with greater chemical competition control and greater fertilization for rapid growth may make sense, depending on biomass prices. However, forestry BMPs have not been tested for SRWCs with greater biomass utilization, more bare ground, and more pesticide and fertilizer application for more rapid growth. In the early 2000s, several states developed woody biomass BMPs, but without the aid of studies to guide BMP development. Our goal was to test current BMPs against the potential hydrologic and water quality issues created by short-rotation wood production with higher rates of herbicide and fertilizer application than used in traditional pine forestry and determine if and what refinements to BMPs are needed for high-intensity SRWCs.

Responses to Previous Reviewers

Reviewer comment: *How does what this project is doing differ from existing practice (I see on reviewing comments from the 2015 review another reader had similar questions)? Pine may be harvested at an earlier age if it is merchantable as a bioenergy product than if it is to be marketed as roundwood, but why would one grow it differently? Perhaps there are reasons (density of wood?), and operating on shorter rotations would presumably involve more frequent land rotations, but it's not clear to me how important these differences are.*

Response: Regarding the question on the differences between SRWC vs conventional forestry, the woody bioenergy feedstock market can be supplied by tops and limbs harvested from traditionally managed stands, and also by SRWCs grown specifically for this market. If there is a sufficient price for woody feedstocks, short rotation silviculture makes sense because the trees are harvested at the point of fastest average growth rate, but before the stems reach the quality necessary for pulp or lumber production. Pulp and sawtimber stands achieve economic maturity later and thus better rates of return for silvicultural investments are achieved later in the cycle. From an environmental standpoint, the major difference between the systems is greater weed control and fertilization prior to crown closure and more frequent ground disturbance in the short-rotation system. The big logistic/operations benefit with SRWCs is the ability to generate sufficient bioenergy feedstock with a nominal transport distance of 50 miles (~average maximum radius where stumpage is positive). For example, 80% of the required biomass for the Ameresco facility can be supplied by 20-25,000 acres of SRWCs, which is a small portion of the land base within 50 miles. Using residues from logging demands 5-10 times the area. Although operation of a facility on residues is possible, it demands other marketable products and mills plus adequate land in management.

The advent of intensive SRWC production for bioenergy raised new forest sustainability and BMP issues for which the traditional forestry BMPs were not designed. Biomass removal and more frequent rotations create the possibility of increased occurrence of overland flow and associated transport of sediments, nutrients, and herbicides and also questions about the effects on carbon storage and fluxes. Specifically, does additional biomass removal reduce soil carbon stocks or does accelerated growth increase soil carbon stocks? Thus, woody biomass production and harvest raises new questions that have not been previously addressed with watershed-scale studies: Are current forestry BMPs sufficient for protecting soil, water, and habitat quality when timber extraction also includes biomass harvest, more frequent harvest, and increased chemical applications? If not, how should BMPs be revised to ensure the sustainability of woody biomass production?

Our study seeks to quantify water, soil, and productivity changes associated with the most intensive woody biomass system, and thus we selected a short rotation system. This type of research has not been done at an operational scale and current forestry BMPs as applied to biomass harvest and production are untested at watershed scales over multiple rotations. There have been some studies investigating the effects of harvest of SRWCs, but no watershed scale studies focused on the entire production cycle, including multiple fertilizer and herbicide applications. There have also been several studies in the southeastern US that have investigated the environmental effects of growing pine for timber, but because of the differences in production for bioenergy vs. timber, it is not known whether the findings from these studies are directly applicable to SRWCs.

Publications

- Caldwell, P. V., C. R. Jackson, C. F. Miniat, S. E. Younger, J. A. Vining, J. J. McDonnell, and D. P. Aubrey. 2018. “Woody bioenergy crop selection can have large effects on water yield: A southeastern United States case study.” *Biomass and Bioenergy* 117: 180–189.
- Drover, D. R., C. R. Jackson, M. Bitew, and E. Du. 2015. “Effects of DEM scale on the spatial distribution of the TOPMODEL topographic wetness index and its correlations to watershed characteristics.” HESSD MS No.: hess-2015-275 MS. (HESSD is the online discussion forum for *Hydrologic and Earth Systems Science*).
- Du, E., C. R. Jackson, J. Klaus, J. J. McDonnell, N. A. Griffiths, M. F. Williamson, J. L. Greco, and M. Bitew. 2016. “Interflow dynamics on a low relief hillslope: Lots of fill, little spill.” *Journal of Hydrology* 534: 645–658.
- Griffiths, N. A., B. M. Rau, K. B. Vaché, G. Starr, M. M. Bitew, D. P. Aubrey, J. A. Martin, E. Benton, and C. R. Jackson. 2018. “Environmental effects of short rotation woody crops for bioenergy: What is and isn’t known.” *GCB Bioenergy.* DOI:10.1111/gcbb.12536.
- Griffiths, N. A., C. R. Jackson, M. M. Bitew, A. M. Fortner, K. L. Fouts, K. McCracken, J. R. Phillips. 2017. “Water quality effects of short-rotation pine management for bioenergy feedstocks in the southeastern United States.” *Journal of Forest Ecology and Management* 400: 181–198.
- Griffiths, N. A., C. R. Jackson, J. J. McDonnell, J. Klaus, E. Du, and M. Bitew. 2016. “Dual nitrate isotopes clarify the role of biological processing and hydrologic flowpaths on nitrogen cycling in subtropical low-gradient watersheds.” *Journal of Geophysical Research Biogeosciences* 121: 422–437.
- Jackson, C. R., M. Bitew, and E. Du. 2014. “When interflow also percolates: Downslope travel distances and hillslope process zones.” Invited Commentary. *Hydrological Processes* 28: 3195–3200.
- Jackson, C. R., E. Du, J. Klaus, N. A. Griffiths, M. Bitew and J. J. McDonnell. 2016. “Interactions among hydraulic conductivity distributions, subsurface topography, and transport thresholds revealed by a multi-tracer hillslope irrigation experiment.” *Water Resources Research* 52: 6186–6206.
- Klaus, J., and C. R. Jackson. 2018. “Interflow is not binary: A continuous shallow perched layer does not imply continuous connectivity.” *Water Resources Research* 54:5921-532.
- Klaus, J., J. J. McDonnell, C. R. Jackson, E. Du, and N. A. Griffiths. 2015. “Where does streamwater come from in low relief forested watersheds? A dual isotope approach.” *Hydrology and Earth Systems Science* 19: 125–135.
- McDonnell, J. J., J. Evaristo, K. D. Bladon, J. Buttle, I. F. Creed, S. F. Dymond, G. Grant, A. Iroume, C. R. Jackson, J. A. Jones, T. Maness, K. J. McGuire, D. F. Scott, C. Segura, R. C. Sidle, and C. Tague. 2018. “Water sustainability and watershed storage.” Commentary. *Nature Sustainability* 1: 378–379.
- Millar, C., D. Pratt, D. J. Schneider, and J. J. McDonnell. 2018. “A comparison of extraction systems for plant water stable isotope analysis.” *Rapid Communications in Mass Spectrometry* 32: 1031–1044.

OAK RIDGE National Laboratory

Presentations (FY17-FY19)

- Aubrey, D. P., C. R. Jackson, J. J. McDonnell, C. R. Miniat, P. V. Caldwell, and S. E. Younger. 2017. "Hydrologic budgets for short rotation loblolly pine and *Eucalyptus*." USDA-NIFA AFRI Sustainable Bioenergy Annual Project Director Meeting, Tampa, FL.
- Bitew, M. M., C. R. Jackson, K. B. Vaché, N. Griffiths, G. Starr, J. McDonnell, B. Rau, S. E. Younger, and K. Fouts. 2016. "Water quantity and water quality impacts of intensive woody biomass feedstock production in the southeastern USA." American Geophysical Union Annual Meeting, December 12–16, 2016, San Francisco, CA.
- Bitew, M. M., C. R. Jackson, K. Vaché, J. J. McDonnell, N. Griffiths, G. Starr, S. Younger, K. Fouts, and B. Rau. 2016. "Modeling hydrologic impacts of intensive woody biomass feedstock production in the southeastern U.S." Short Rotation Woody Crop Science and Technology in an Uncertain Global Marketplace. 11th Biennial Short Rotation Woody Crops Operations Working Group Conference, October 11–13, 2016, Fort Pierce, FL.
- Brockman, L. E., S. E. Younger, C. R. Jackson, J. J. McDonnell, and K. F. Janzen. 2017. "Differential soil water sourcing of managed loblolly pine and sweetgum revealed by stable isotopes in the Upper Coastal Plain, USA." American Geophysical Union Meeting, December 11–15, 2017, New Orleans, LA.
- Griffiths, N. A., C. R. Jackson, G. Starr, B. Rau, K. B. Vaché, J. J. McDonnell, M. Bitew, E. Du, J. Klaus, J. Jeffers, K. Fouts, A. Fortner, K. McCracken, and J. Phillips. 2018. "Experimental effects of short-rotation pine production for bioenergy: Findings from a watershed experiment." Society of American Foresters National Convention, October 3–7, 2018, Portland, OR.
- Griffiths, N. A. 2016. "Utilizing long-term ecosystem experiments to examine the effects of human activities on hydrology and biogeochemical cycling." Robert B. Annis Water Resources Institute, Grand Valley State University, November 11, 2016, Muskegon, MI. Invited seminar.
- Jackson, C. R. 2017. "Shallow subsurface stormflow (interflow): Functioning to extend variable source areas upslope." Luxembourg Institute of Science and Technology, May 2, 2017, Belval, Luxembourg. Invited seminar.
- Jackson, C. R. 2016. "Conceptual, theoretical, and philosophical considerations in water quality modeling." Tianjin University of Science and Technology, December 9, 2016, Tianjin, China. Invited seminar.
- Jeffers, J. B., C. R. Jackson, B. Rau, C. Pringle, and C. Matteson. 2018. "Dissolved gas concentrations in shallow groundwater as evidence of nitrate reduction through a riparian zone adjacent to a short-rotation woody crop stand." Warnell Graduate Student Symposium, January 31–February 2, 2018, Athens, GA.
- Jeffers, J. B., C. R. Jackson, B. M. Rau, C. M. Pringle, and C. T. Matteson. 2017. "In situ groundwater denitrification in a riparian zone of a short-rotation woody crop experimental watershed." Bottomland and Swamp Forests Symposium, October 31–November 2, 2017, Wilmington, NC.

Oak Ridge National Laboratory

Presentations (FY17-FY19) Continued

- Jeffers, J. B., C. R. Jackson, B. Rau, C. Pringle, and C. Matteson. 2017. “In situ groundwater denitrification in the riparian zone of a short-rotation woody crop experimental watershed.” American Geophysical Union Meeting, December 11–15, 2017, New Orleans, LA.
- Klaus, J., and C. R. Jackson. 2018. “How far does interflow travel down slope: A comparison study across seventeen hillslopes.” 17th Biennial Conference Euromediterranean Network of Experimental and Representative Basins, September 11–14, 2018, Darmstadt, Germany.
- Klaus, J., and C. R. Jackson. 2018. “Downslope travel distance and hydrological connectivity: On the role of interflow in different landscapes.” European Geosciences Union General Assembly, April 8–13, 2018, Vienna, Austria.
- Rau, B. M., N. Griffiths, C. R. Jackson, and J. Blake. 2016. “Nitrogen cycling in short rotation pine.” Soil Science Society of America Annual Meeting, November 6–10, 2016, Phoenix, AZ.
- Vaché, K. B., M. Bitew, N. A. Griffiths, and C. R. Jackson. 2018. “Hydrologic effects of short-rotation woody crops at landscape scales modeled over multiple rotations.” Society of American Foresters National Convention, October 3–7, 2018, Portland, OR.
- Vaché, K. B., J. McDonnell, C. R. Jackson, and M. M. Bitew. 2016. “Observation-based model development for groundwater dominated catchments.” American Geophysical Union Annual Meeting, December 12–16, 2016, San Francisco, CA.
- Younger, S. E. and C. R. Jackson. 2017. “Variation of annual ET determined from water budgets across rural southeastern basins differing in forest types.” American Geophysical Union Meeting, December 11–15, 2017, New Orleans, LA.

Abbreviations

- AGM MCP 37 – Loblolly pine seedling family
- B – Bowen ratio (unitless)
- BETO – Bioenergy Technologies Office
- BMPs – Best Management Practices
- DAP – Diammonium phosphate (fertilizer)
- Envision – Distributed watershed model developed for SRS watersheds
- ET – Evapotranspiration
- Fert. – Fertilizer
- Fourmile – Larger watershed that encompasses our 3 study watersheds
- GEE – Gross Ecosystem Exchange
- Hi Int – High intensity forestry (10-year short-rotation) modeling scenario
- Hi Int Ag – High intensity forestry with 50% land in agriculture (modeling scenario)
- KDF – Knowledge Discovery Framework
- LAI – Leaf Area Index (unitless)
- L Int – Low-intensity forestry (35-year rotation) modeling scenario
- MIKESHE – Integrated hydrological model (surface and groundwater)
- MRT – Median residence time
- N – Nitrogen
- NC – North Carolina
- NCASI – National Council for Air and Stream Improvement
- NEE – Net Ecosystem Exchange
- NH_4 – Ammonium
- NO_3 – Nitrate
- N_2O – Nitrous oxide
- N-min – Nitrogen mineralization
- Op. – Operational
- ORNL – Oak Ridge National Laboratory
- ORNL TM 2018-1055: Final project report ID
- R_{eco} – Ecosystem respiration
- REF – Reference watershed
- SC – South Carolina
- SE – Southeastern US
- SMZ – Streamside Management Zone (50 ft buffer between planted areas and stream; hardwood riparian zone)
- SRP – Soluble Reactive Phosphorus
- SRWC – Short-Rotation Woody Crop
- SRS – Savannah River Site
- SWAT – Soil and Water Assessment Tool
- TRT – Treatment watershed
- Veg. – Vegetation
- Watersheds B and C – Treatment watersheds (locations of clear cuts/SRWC production)
- Watershed R – Reference (unmanipulated) watershed
- WUE – Water Use Efficiency

Experiment Progression as seen from Satellite Images

Images from Google maps