2013 DOE Bioenergy Technologies Office (BETO) Project Peer Review

Short Rotation Woody Biomass Sustainability

May 23rd, 2013
Analysis and Sustainability

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Goal Statement

Overall Project Goal:

Use watershed-scale experiments along with a distributed watershed modeling approach to evaluate environmental sustainability relative to selected indicators (water quality, water quantity, soil quality, and productivity) of intensive short-rotation pine practices for bioenergy in the Southeastern U.S.

DOE Bioenergy Technologies Office & Industry Goal:

To understand and promote the positive economic, social, and environmental effects and reduce the potential negative impacts of bioenergy production activities (Sustainability Goal, DOE EERE MYPP Nov 2012).

Quad Chart Overview

Timeline

- Project start date: FY10
- Project end date: FY18 (proposed)
- Percent complete: 30%

Budget

- Years project has been funded: 4 yrs (FY10-FY13)
- Average annual funding: $700,000
- DOE funds received:

	ORNL	UGA/ OSU/ USFS-SR	USFS Cost Share
FY11	$273,000	$640,000	$187,000
FY12	$113,000	$376,000	$193,500
FY13	$225,000	$445,000	$141,500

Barriers

- Sustainability data across the supply chain (St-C). "A fundamental hurdle is the lack of data to evaluate sustainability…"
- Best practices for sustainable bioenergy production (St-E). "Few 'best practices' and sustainable systems defined for the bioenergy supply chain"
- Sustainable Production (Ft-B). "Existing data on the productivity and environmental effects of energy crop production are not adequate to support life-cycle analysis of biorefinery systems"

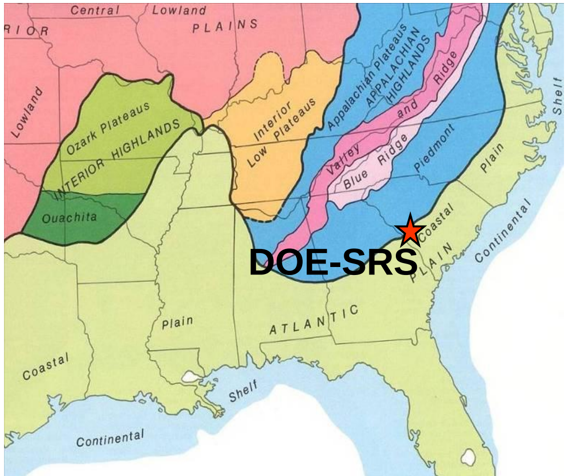
Partners

- Collaborators:
  - USFS-SR: Carl Trettin
  - OSU: Kellie Vache
  - U Saskatchewan: Julian Klaus
  - UGA: Enhao Du, Ben Morris
- Project management: ORNL

Project Overview

History: Initiated in 2009-2010. Watersheds (600 hectares of old-field forest) set aside by SRS for environmental R&D of intensive biomass to support regional sustainable bioenergy feedstock supplies.

Context: The Southeastern U.S. will be a dominant feedstock source for bioenergy. High-yield targets have been demonstrated experimentally. Stream, soil, and groundwater quality impacts of these practices (multi-year weed control & fertilization) coupled with advanced genetics have not been evaluated <u>in combination at the watershed scale</u>. Current forestry BMPs in the S.E. have not been tested on practices of this intensity to assess the incremental impacts for sustainability indicators.



Southern Forest Resource Assessment, 2002

Objectives: 1) assess the effects of intensive practices on bioenergy sustainability indicators (watershed hydrology, water quality, soil quality, and productivity) relative to existing standards, 2) integrate dominant hydrologic processes across scales, and 3) apply distributed modeling to generalize and interpret results and suggest mitigation strategies.

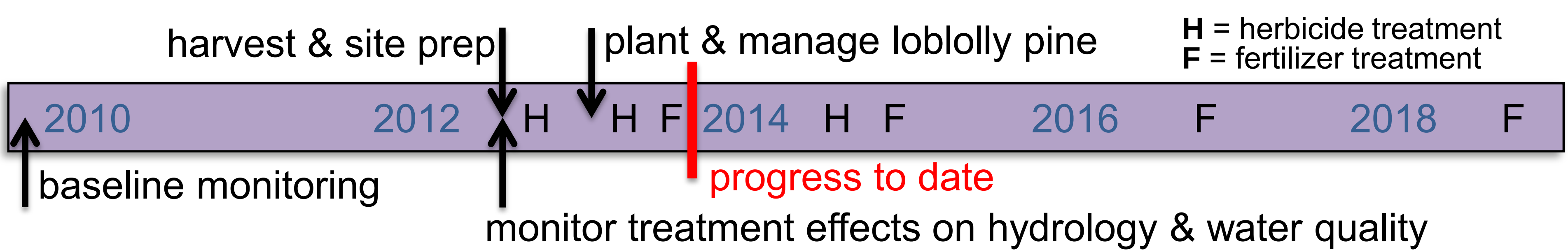
Overall Technical Approach

The experiment uses a before-after control-intervention (BACI) design involving the study of three adjacent watersheds at the Savannah River Site.

- Intensive silviculture practices are "state of the art" for woody crops and include sub-soiling, multiple herbicide applications, annual fertilization, and advanced genetic material.
- Monitoring of hydrology, stream and groundwater quality, and soil quality allows for direct assessment of stream, groundwater, and soil quality at an operational scale.
- Distributed modeling allows integration of water flowpaths and mass balances across all time scales at the plot, hillslope, and watershed spatial scales to generalize results to the Coastal Plains area of the Southeastern U.S., an area projected to be a dominant contributor to woody biomass feedstocks for bioenergy production.
- Process-level field observations on water isotopes, subsurface flow, and nitrogen cycling, coupled with precision spatial data will enhance interpretation of model results.

Process Overview/Timeline

- 2010-2011: site selection, determine experimental treatments, develop silviculture plan.
- 2010-2012: initiate watershed characterization, determine baseline hydrology and water quality conditions in all 3 watersheds.
- 2012: implement short-rotation pine treatments in 2 watersheds (convert ~40% of extant forest to short-rotation pine).
- 2012-2018: assess short and longer-term impacts of treatments on hydrology and water quality, compare impacts to baseline values and the reference watershed, use results to evaluate existing BMPs and regulatory standards.
- 2010-2018: Develop and inform hillslope- and watershed-scale hydrologic models using hydrology data. Model development and application to bioenergy feedstock sustainability in the S.E. will occur throughout study.
- 2010-2018: Disseminate results through presentations and publications.



Overall Management Approach

Division of tasks: water quality (ORNL), hydrology (UGA), hydrologic modeling (OSU), stable isotopes (US), operational forestry practices (USFS-SR), and forest nutrition (USFS-SR).

Project management:

- Monthly conference calls to discuss progress.
- Bi-annual project meetings (Jan 2013 at SRS, July 2012 & 2011 at OSU).
- On-site field technician (UGA) collects samples and maintains equipment.

FY2012-13 Milestones divided by tasks to monitor progress:

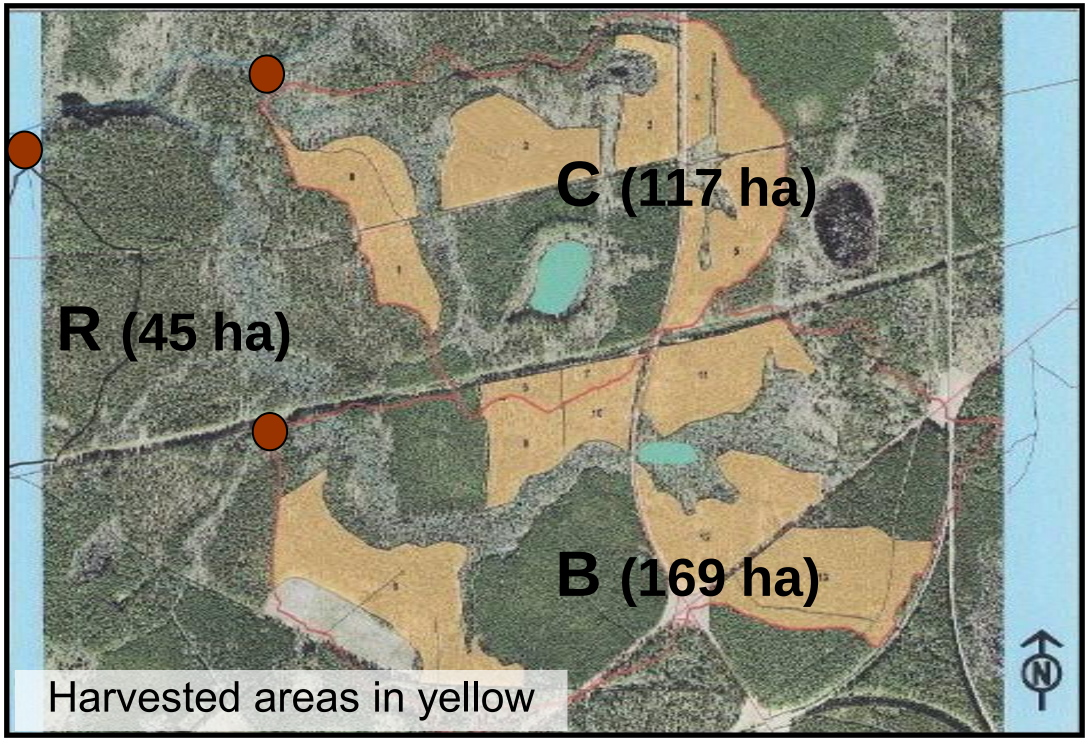
Milestone	Due Date	Group(s) Responsible	Status
Complete analysis of water quality samples collected prior to establishing pine	12/31/11	ORNL	100% complete
Complete characterization of soil properties on treatment hillslopes	3/31/12	UGA	100% complete
Complete harvesting and removal of timber from treatment watersheds	6/30/12	USFS-SR	100% complete
Complete watershed model parameterization across the Fourmile Watershed	9/30/12	OSU	100% complete
Analyze FY12 water quality samples to test effects of harvest/site preparation	12/31/12	ORNL	100% complete
Complete pine plantation and initiate vegetation and nitrogen cycle monitoring	3/31/13	USFS-SR	100% complete
Submit a manuscript on hydrology of reference watershed	6/30/13	UGA	90% complete
Use hydrologic models to evaluate the potential effects of different forest management practices on the hydrological function of the study watersheds	9/30/13	OSU	25% complete

Progress on Experimental Treatments

- Three large old-field forested watersheds, one reference (R) and two treatment (B, C), with intermittent stream and ephemeral channels. Acquired and integrated detailed soils, vegetation, LiDAR topography, groundwater, streams, and meteorological databases.

Infrastructure:

- Three stream flumes
- 20 deep groundwater wells
- Site weather station and 10 sub-canopy rain gauges
- >12 stream side piezometers
- 5 subsurface trench collectors with hillslope instrumentation
- 12 nitrogen budget, soil quality, and productivity plots



Intensive pine management practices following harvest on 40+% of Watersheds B and C (130 ha total).

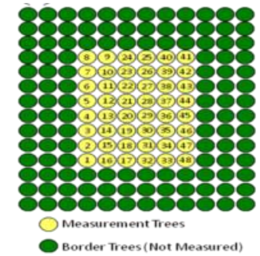
Progress on Harvest & Silviculture Treatments

<u>All milestones completed since 2011 peer review:</u>

- Jan-May 2012: Harvest (40+% of area), including 20 Mg/ha of residues removed for bioenergy.
- Summer/fall 2012: Ripping/sub-soiling.
- Sept 2012: Imazapyr-glyphosate applied.
- Jan-Feb 2013: Planting of loblolly pine (AGM MCP 37 =70%> standard Southeast reference).
- Mar 2013: Herbaceous weed control (sulfometuron methyl-imazapyr).
- April 2013: Fertilization with diammonium phosphate.
- Contract awarded for herbaceous weed control in Feb/Mar 2014.
- Fertilization of plantations with N scheduled for 2014 & 2015.
- Delivered cost is estimated at $60/dry ton, compared with MYPP of $80/dry ton.

Progress on the Nitrogen Budget, Soil Quality, and Productivity Study

- Objective: Quantify soil-vegetation N budget, soil quality, and productivity as a function of resource availability and sink strengths.
- All milestones for FY12 & FY13.
  - Established 8 replications of 5 treatments plus 4 forest controls.
  - Planted seedlings.
  - Collected baseline soil samples for physical & chemical analysis.
  - Installed soil N resin lysimeters & mineralization incubators.
  - Applied initial weed control & fertilization concurrently with large-scale operations.



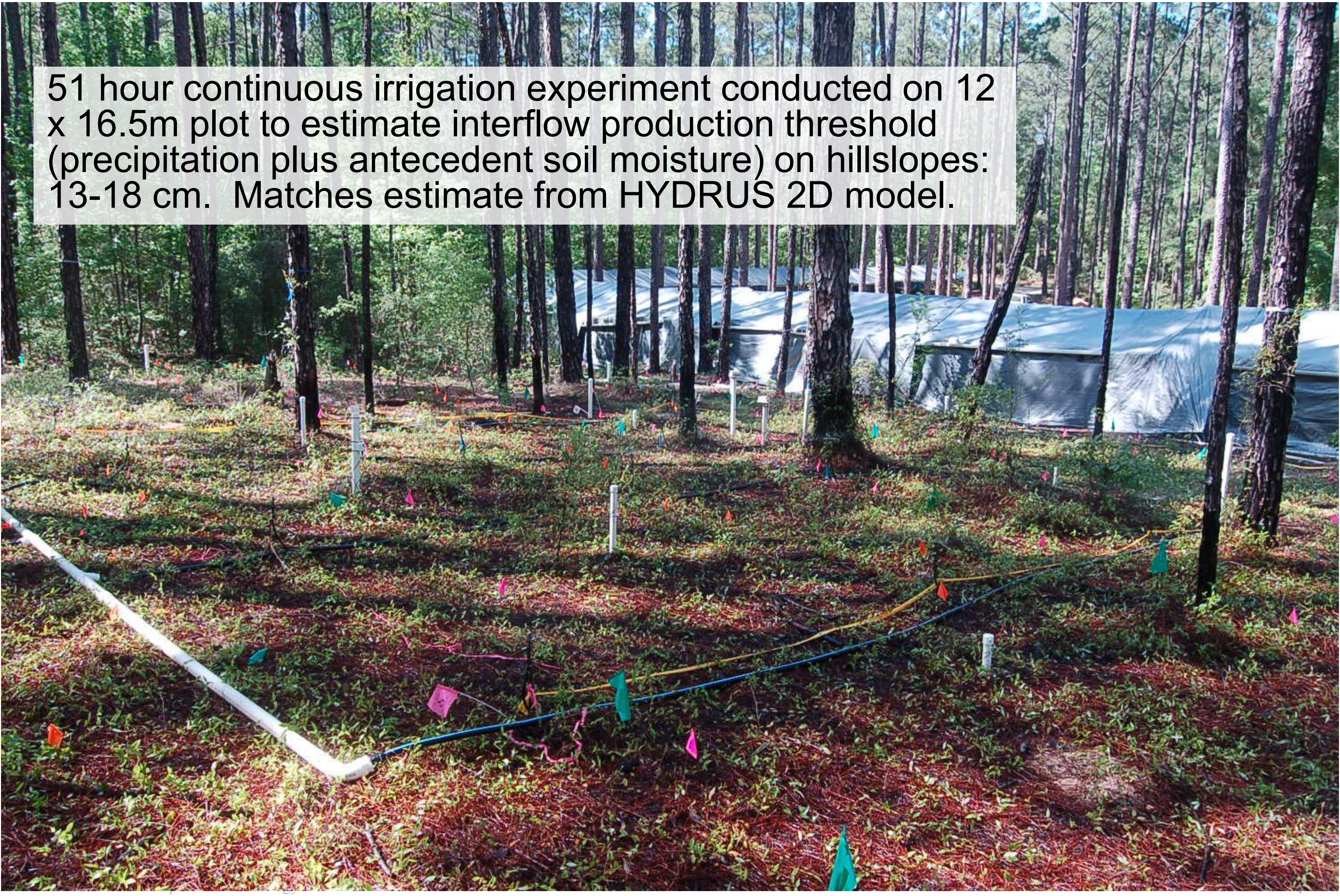
TRT1 Elite genetics No nutrients No herbicides Op. density	TRT2 Elite genetics No nutrients Op. herbicides Op. density	TRT3 Elite genetics 1/2 nutrients Op. herbicides Op. density
TRT4 Elite genetics Op. nutrients Op. herbicides Op. density	TRT5 Elite genetics Op. nutrients Op. herbicides High density	

Field Hydrology Results

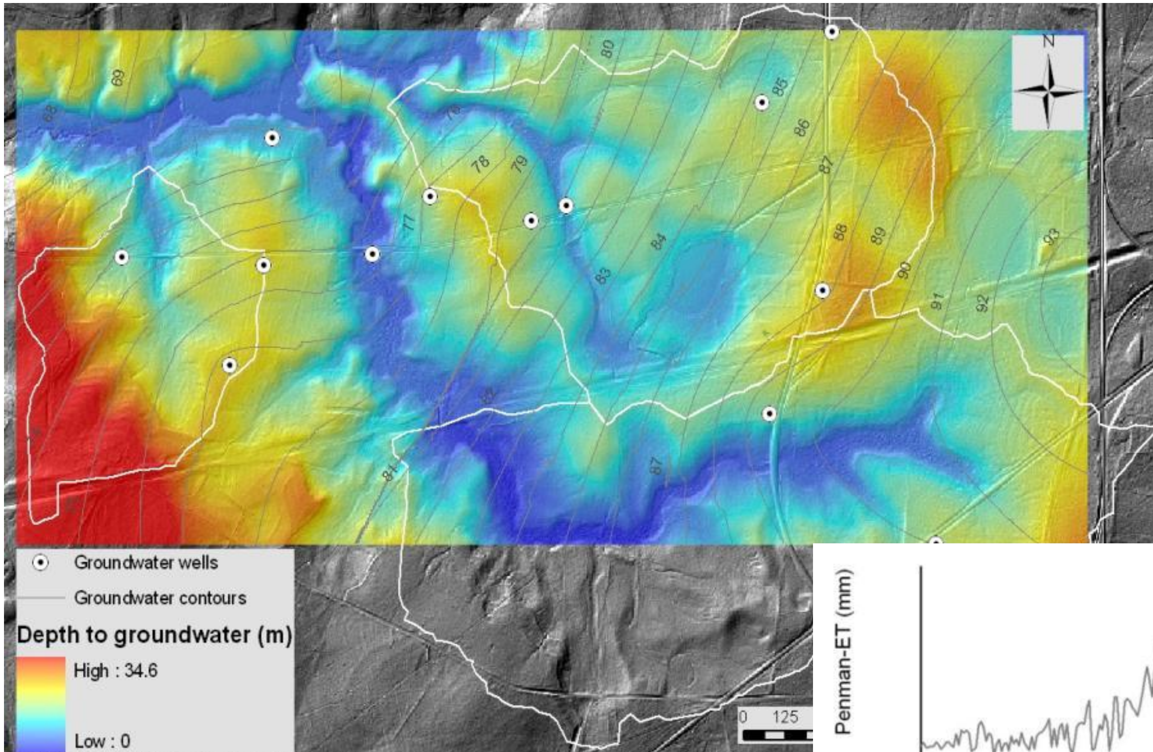
- Objectives:
  - Identify and characterize dominant hydrologic processes and streamflow generation pathways.
  - Develop time series of flows, moisture levels, and groundwater levels with which to inform and test hydrologic models for simulating management scenarios.
  - Use stable isotopes and water chemistry to relate streamflow to hillslope, riparian, and ground water.
- All milestones completed for FY12. FY13 Q3 milestone 90% complete (manuscript submission due 6/30/13).
- Key hydrology findings:
  - Experiments and models reveal a high precipitation and moisture threshold for producing interflow from the hillslopes.
  - Depths to groundwater and groundwater behavior contrast sharply between riparian areas and hillslopes.
  - Streamflow is chemically similar to riparian water, not hillslope water.
  - Inference – groundwater will be the dominant connection between silvicultural activities and streams.

Field Hydrology Results

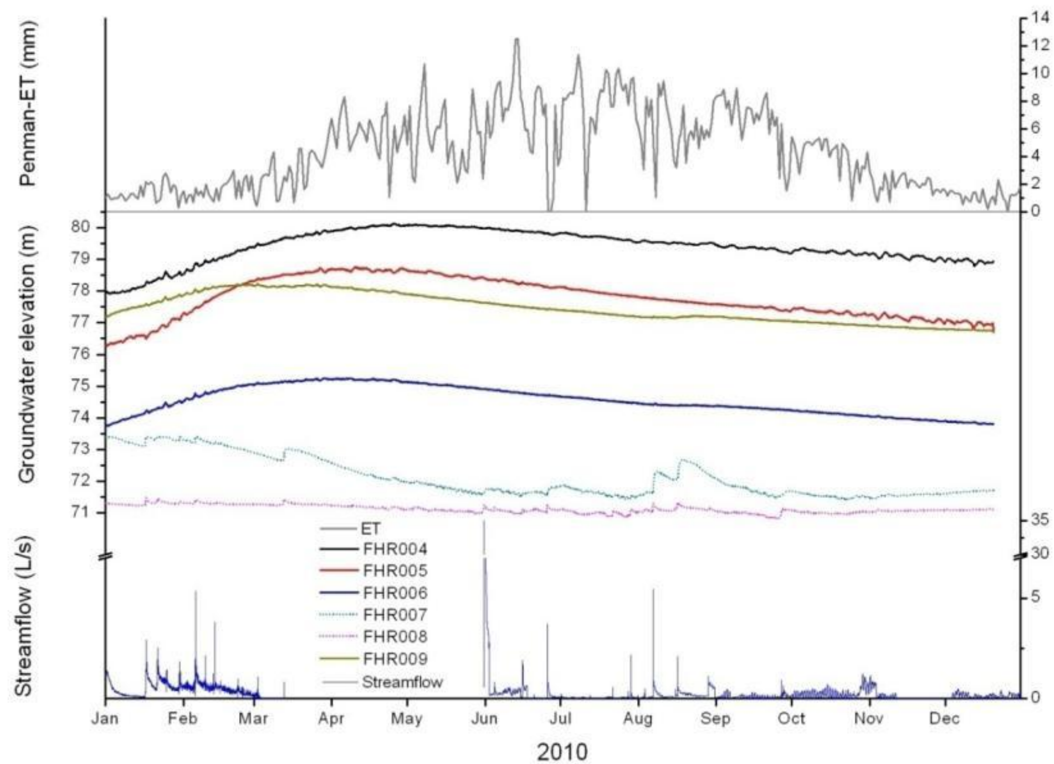
51 hour continuous irrigation experiment conducted on 12 x 16.5m plot to estimate interflow production threshold (precipitation plus antecedent soil moisture) on hillslopes: 13-18 cm. Matches estimate from HYDRUS 2D model.



Field Hydrology Results

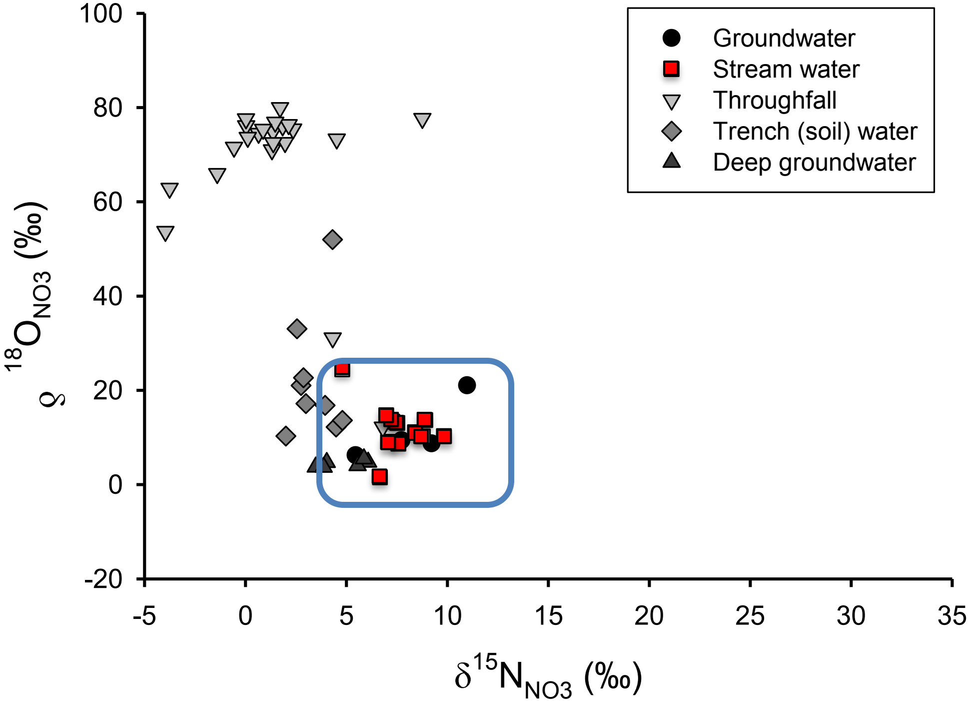


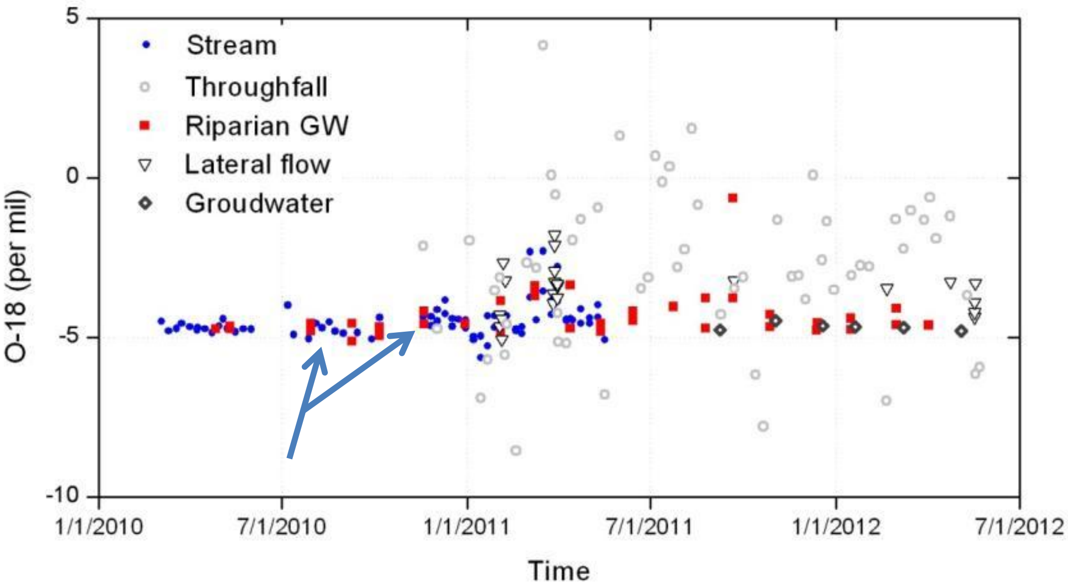
- Depth-to-groundwater map estimated from well measurements in October 2012. Depths vary from 0 m at Fourmile and lower part of the 1st order streams to 35 m at ridgetops of the R watershed.



- The ridge and mid-slope wells (solid lines) fluctuate seasonally and lag water demand (ET) by months.
- The riparian wells respond more quickly to ET and are more closely linked to streamflow regimes.

Field Hydrology Results

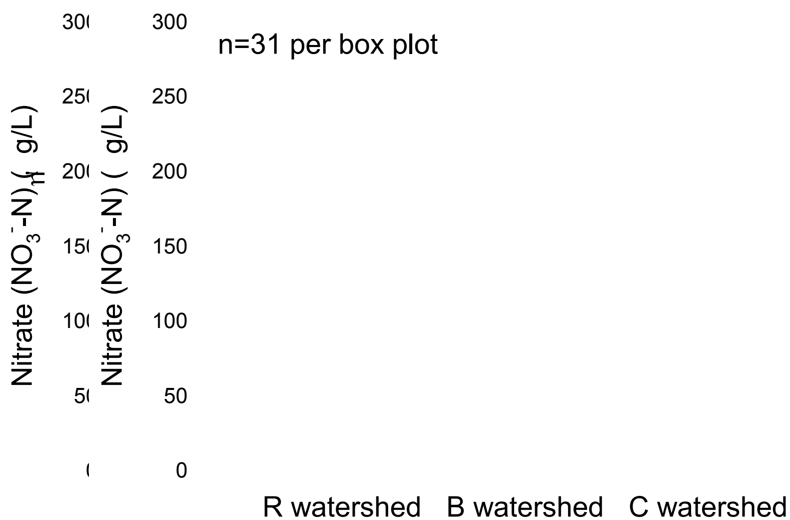


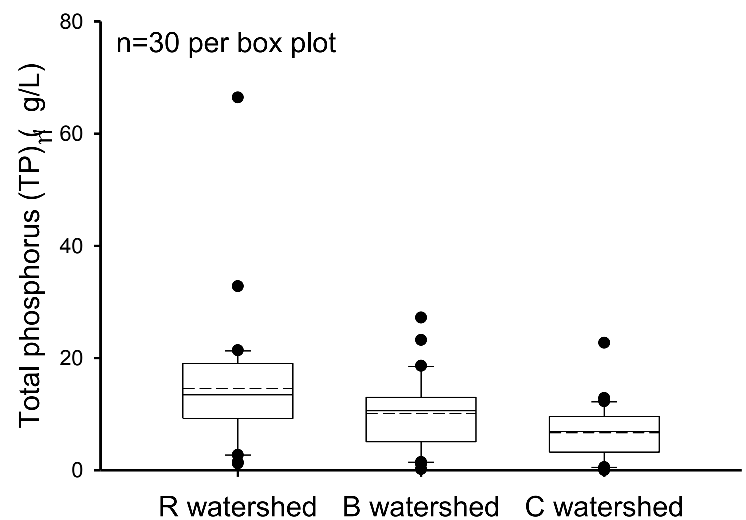


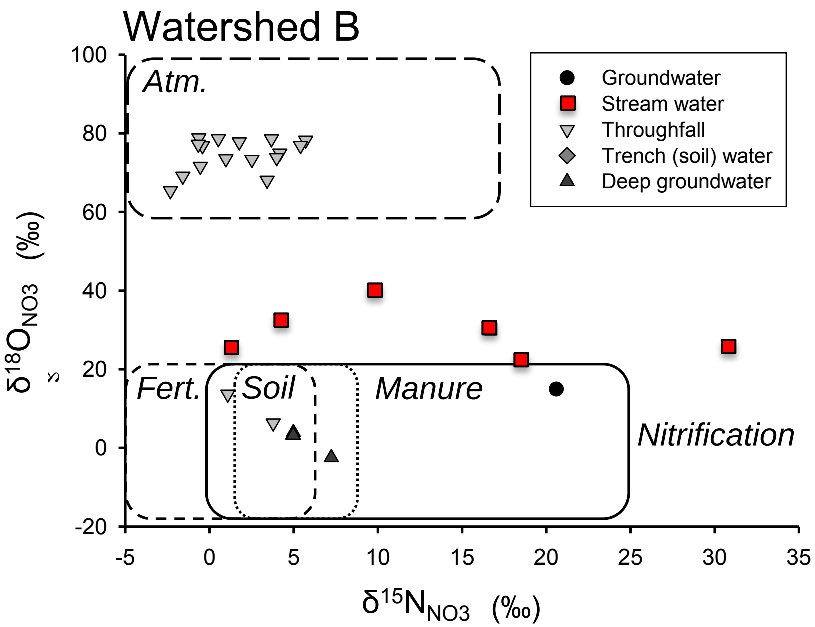
- Similar values of ^{15}N and ^{18}O in stream and groundwater suggest that riparian groundwater is a source of stream nitrate in Watershed R.
- Time series of ^{18}O in streamflow, riparian piezometer, subsurface stormflow, riparian piezometers, and groundwater wells in Watershed R. Throughfall exhibits strong variability than is not observable in streamflow. Streamflow is usually very close to the isotopic composition of the riparian groundwater, while the observed hillslope (lateral flow) isotopic composition exhibited strong differences compared to streamflow.

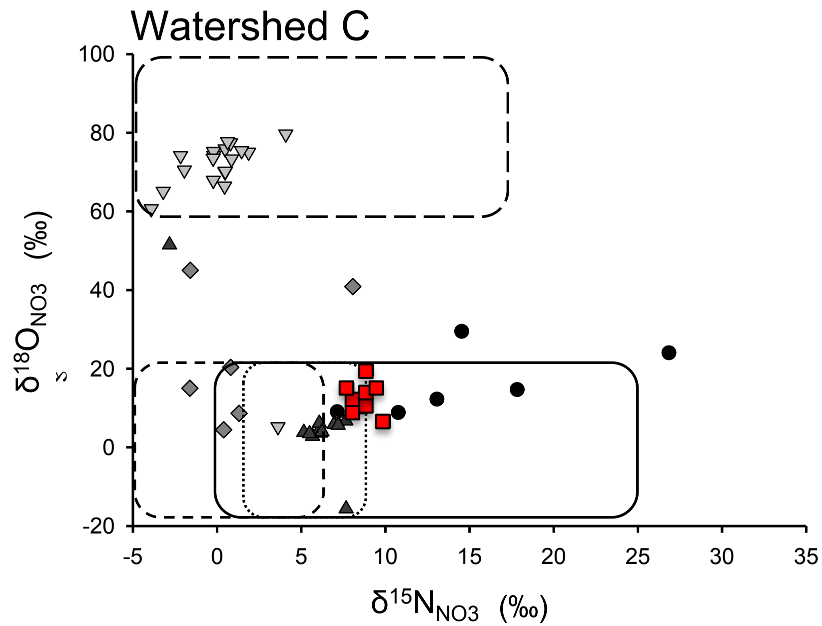
Water Quality Results

- Objectives:
  - Determine baseline water quality in the 3 study watersheds.
  - Examine the short- and long-term effects of conversion to and management of short-rotation woody biomass (i.e., harvest, site preparation, planting) on water quality.
- All milestones completed for FY12 & FY13.
- Key water quality findings:
  - Baseline nitrogen and phosphorus concentrations low.
  - A combination of riparian buffers and a disconnect between the hillslopes and the streams suggests nitrate contamination of groundwater may be









- Stream water nitrate appears to originate from the atmosphere and groundwater due to similar ^{15}N and ^{18}O signatures in nitrate.
- Nitrate is mobile, but not much evidence that nitrate on the hillslope is moving into the streams.
- Nitrate contamination of groundwater may be most important in these low-gradient watersheds.
- Nitrate concentrations in deep groundwater similar before and after harvest/site preparation. Monthly sampling will continue after fertilization.

Water Quality Results: Phosphorus and Herbicides

Phosphorus:

- Baseline phosphorus concentrations are low.
- Phosphorus concentrations in deep and riparian groundwater similar before and after harvest/site preparation. Streams were dry for much of 2011, and water samples collected in 2012 are currently being analyzed.

Herbicides:

- Two herbicide applications to the treatment areas to date (Sept 2012 & March 2013).
- Monthly sampling of streams (baseflow and storm sampling), riparian groundwater, and deep groundwater.
- Herbicides (imazapyr, glyphosate, sulfometuron methyl) below or at (3 of 152 samples) detection (detection limit = 1-2 µg/L).

Hydrologic Modeling Results

Objectives:

- Capture the dominant hydrologic processes identified as part of field hydrology component in numerical models.
- Test models for simulating management scenarios using observed time series of flows, moisture levels, and groundwater levels.
- Model relationships between forest cover, meteorological variables, soil moisture, and groundwater dynamics.
- Evaluate influence of biomass harvest on the hydrological cycle at local and regional scales.
- Use stable isotopes and water chemistry to relate streamflow to hillslope, riparian, and groundwater.

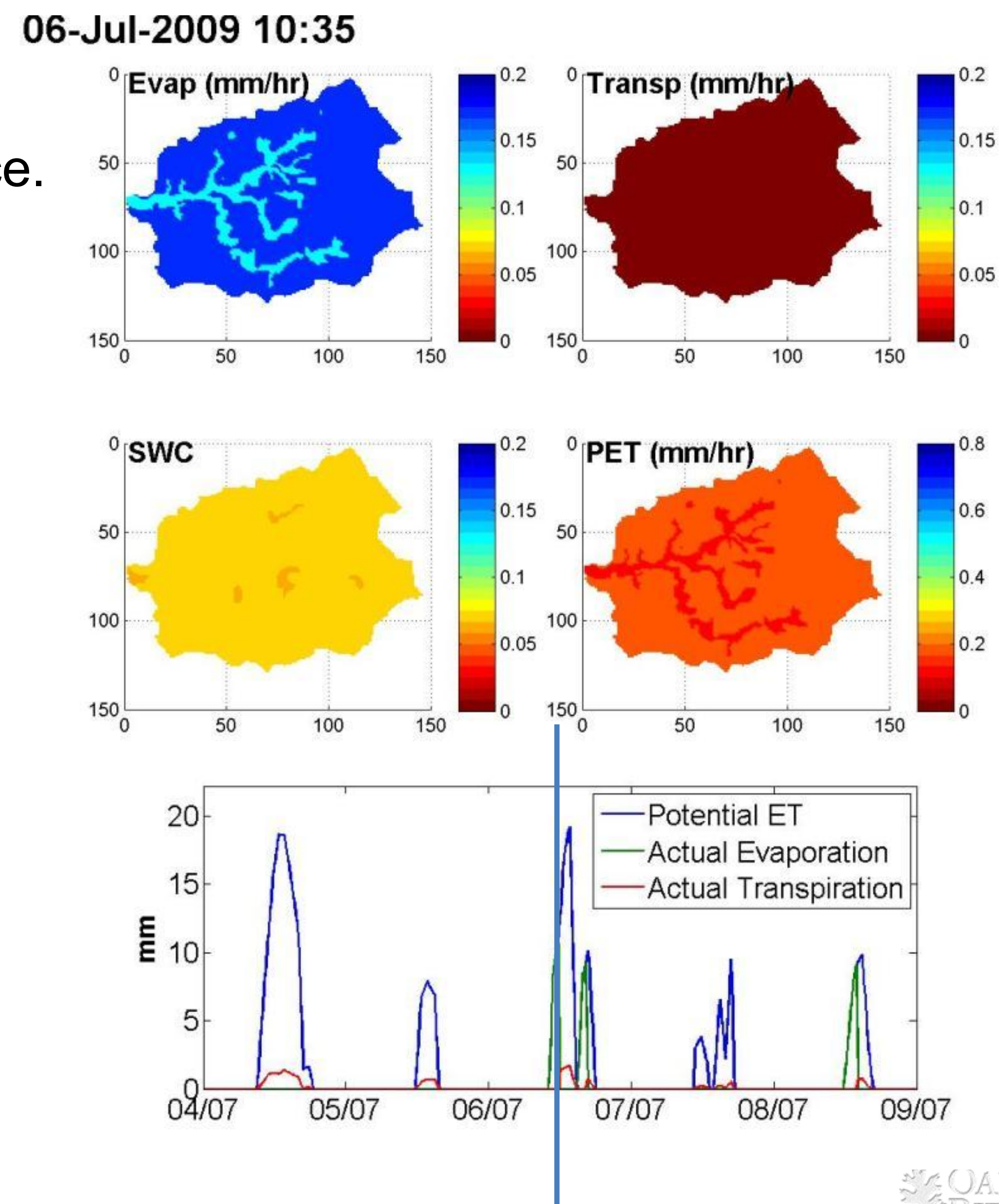
- All FY12 milestones completed. FY13 Q4 milestone 25% complete (use model to evaluate effects of different forestry management practices, due 9/30/13).

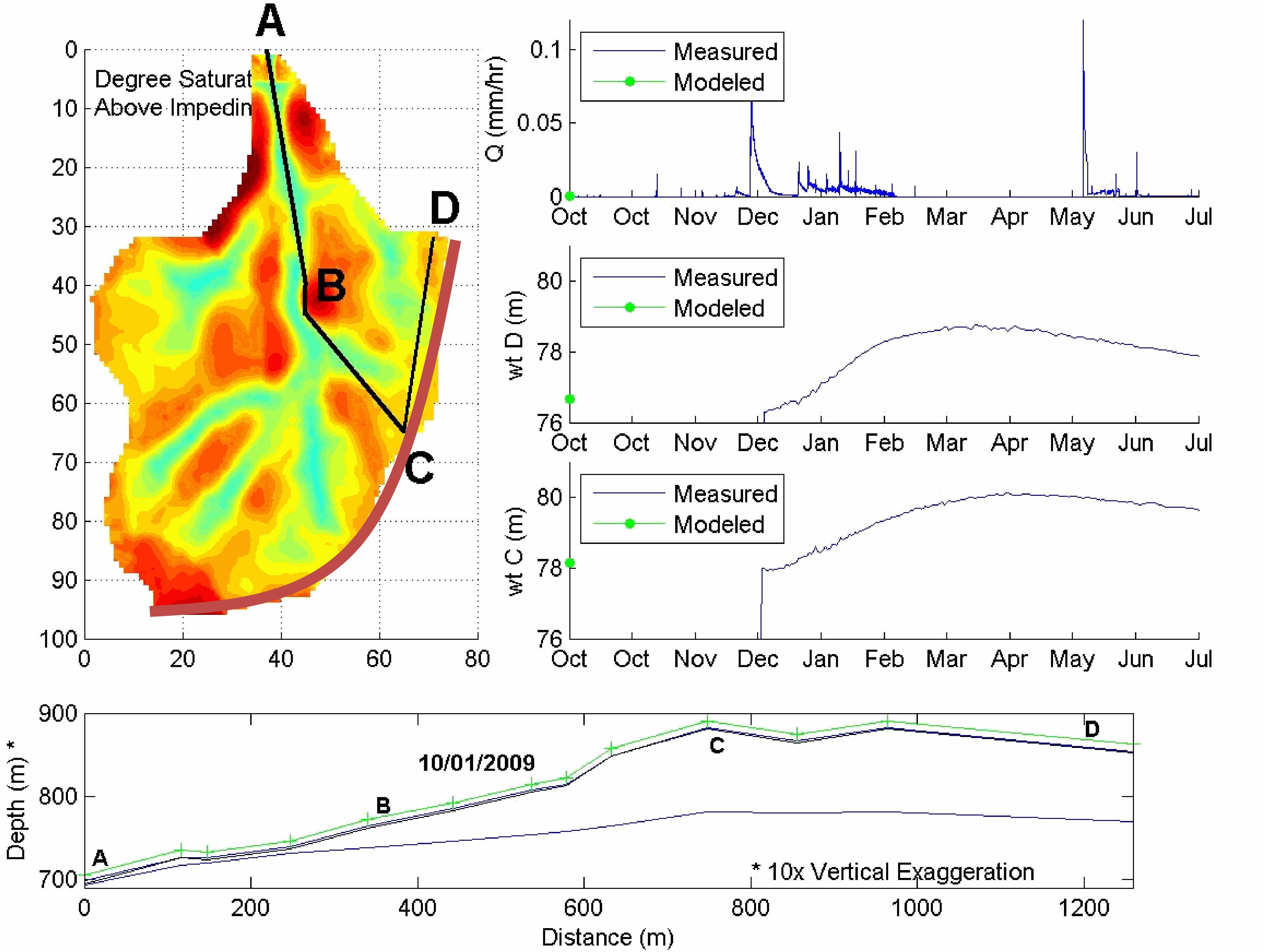
Key modeling findings:

- Distributed model consistent with observations, including high precipitation and moisture threshold to produce interflow from the slopes, and significant differences in groundwater depth between riparian and hillslope areas.
- A conservative tracer model has been included. The model is being tested against isotope data and will be used to evaluate residence times and the potential for transport control of water quality issues.

Hydrologic Modeling Results

- Physically-based modeling to capture detailed energy balance.
- Separate calculations of evaporation, transpiration, and bare soil evaporation.
  - Relevant to silvicultural practices.
- Variation in space and time.
  - Sensitive to the spatial arrangement of processes and management.





A
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Depth (m) *
Distance (m)
* 10x Vertical Exaggeration

Relevance

- Sustainable feedstock production of intensive bioenergy systems is an important goal of the BETO MYPP (Nov 2012). Protection of water and soil quality is critical in the Southeastern U.S.
- This project will directly assess key sustainability indicators (water quality, water quantity, soil quality and productivity) resulting from high-yield woody crops technology using an operational-scale experiment.
- This project will demonstrate whether current forestry BMPs are adequate to protect hydrology, water quality, and soil quality when applying this technology and it will inform State water quality foresters and EPA on any potential incremental effects vis-à-vis conventional intensive silviculture.
- This project will expand and generalize results through the application of a distributed hydrologic model and will interpret combined effects of high-yield woody crops for bioenergy in terms of hydrologic processes across scales.

Critical Success Factors

Success Factors:

- Results will provide detailed analysis of the environmental sustainability of intensive short-rotation pine for bioenergy by determining the impacts on hydrology, water quality, soil quality, and productivity as key sustainability indicators.
- Results will measure the difference between current environmental baselines and whether current forestry BMPs provide a high degree of protection of waters in the Southeastern U.S.
- Results will advance understanding of hydrologic and chemical processes that can be generalized and interpreted in a more robust modeling framework.
- Results will be published in peer-reviewed journals acceptable to Federal/State regulators and accessible to extension personnel. Results will be presented to industry (NCASI), state water quality foresters, EPA.

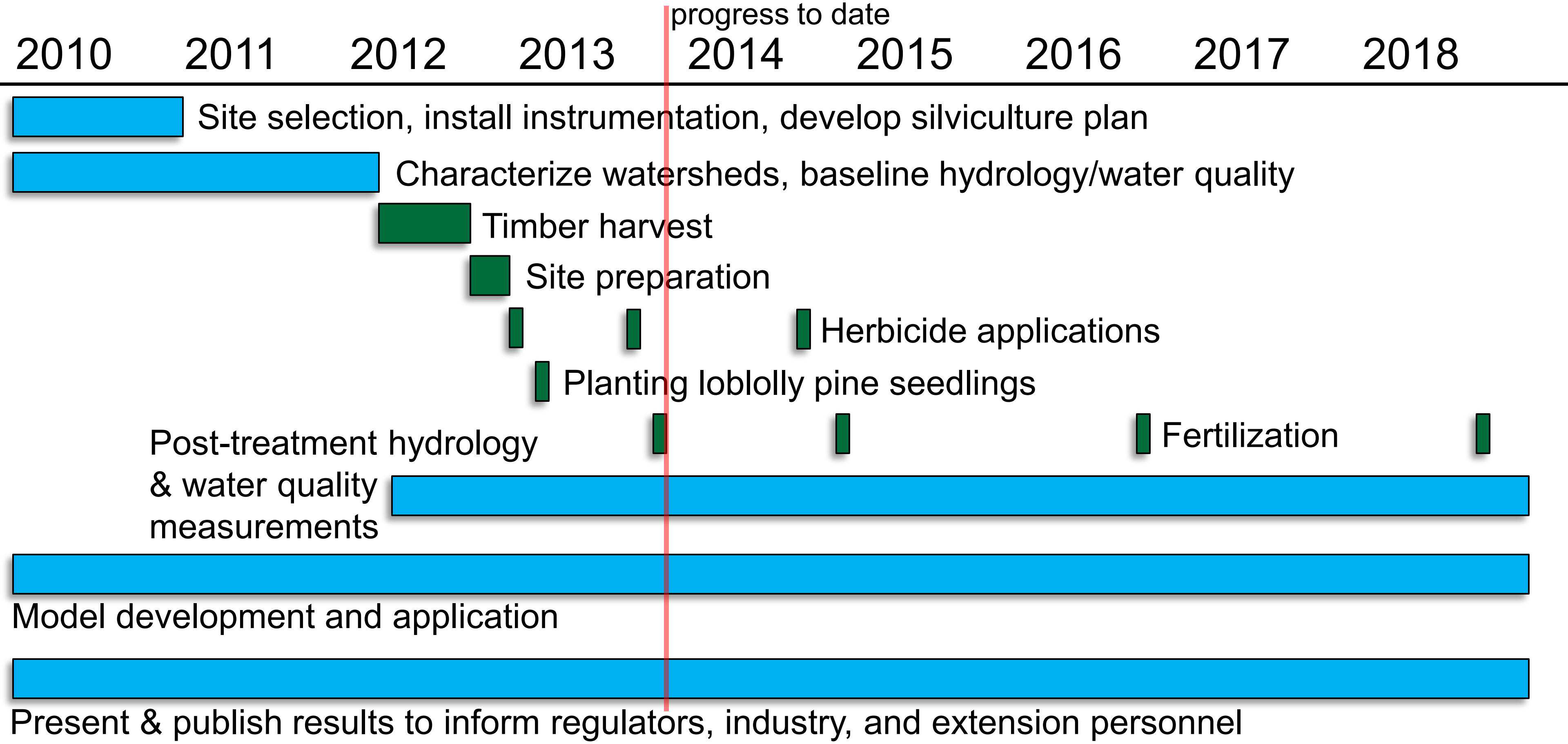
Advancement of Technology:

- Results are expected to validate environmental sustainability of high-yield woody crop production technology and provide a baseline for this technology relative to current BMPs based on existing studies.

Future Work

- Intensive silviculture practices: Complete last herbicide treatment in 2014 and continue periodic applications of nitrogen through 2018.
- Hydrology: Continue measuring water flow and stable isotopes through 2018 to gain insights into dominant flow processes and inform the hydrologic model.
- Hydrologic modeling: Test transferability of model to other watersheds at SRS. Simulate management scenarios across watershed scales.
- Water quality: Continue measuring and analyzing water quality data to determine effects of intensive pine management through 2018.
- Nitrogen study: Measure N leaching & mineralization monthly, and soil properties annually. Initiate annual measurements of above and below ground productivity and nutrient uptake of vegetation through 2018.
- Technology & information transfer: Coordinate & present results to industry (NCASI), state water quality foresters, EPA. Publish results in peer-reviewed journals. Confirm economic analysis related to production, growing, and delivered costs <$60/dry ton.

Future Work: Gantt chart and milestones



- Upcoming FY13 milestones:
  - Submit a manuscript on the hydrology of the reference watershed. Due 6/30/13, 90% complete.
  - Use hydrologic models to evaluate the potential effects of different forest management practices on the hydrological function of the study watersheds. Due 9/30/13, 25% complete.

Summary

- Approach: innovative watershed-scale study assessing the environmental sustainability of short-rotation pine plantations. Integrates hydrology, water quality, and soil quality data in a distributed modeling approach to broaden the applicability and context.
- Technical accomplishments:
  - Extensive depth-to-clay measurements have revealed significant subsurface hillslope storage leading to high interflow threshold.
  - Hydrus 2D modeling and large-scale irrigation experiment have predicted and verified high interflow threshold.
  - Groundwater and streamflow observations coupled with isotopic and chemical data have demonstrated riparian dominance in streamflow.
  - Ground surveys of riparian perimeters have shown rapid reinfiltration of overland flow produced from plantations and no connection to streams.
  - Low pre-project nutrient concentrations, as well as substantial variability between the watersheds has been established.
  - Hydrometric, isotopic, and chemical data have informed the process based modeling.

Summary

- Relevance: directly addresses key sustainability criteria and indicators of MYPP and aligns with targets dates.

- Critical success factors and challenges: results will provide detailed analysis of the environmental sustainability and key sustainability indicators of intensive short-rotation pine for bioenergy, will be published in peer-reviewed journals to inform regulators and extension personnel, and presented to industry (NCASI), state water quality foresters, EPA.

- Future work: continue monitoring to assess short and longer-term impacts of forest conversion on hydrology and water quality, compare impacts to both baseline values and the reference watershed, use results to evaluate existing BMPs and regulatory standards. Continue modeling effort to explore long term implications of higher intensity management and extend the effort to the Coastal Plains region to broaden regional context of the study.

- Technology transfer: directly assesses the adequacy of current BMPs and provides an operational-scale demonstration of this technology. Disseminate results through presentations and publications.

Additional Slides

Responses to Previous Reviewers' Comments

Question: The approach of having two experimental watersheds and one control watershed seems sound, although if there is wide differences or no differences it will be hard to interpret the results. There are strengths to do watershed scale research but with lack of replication it is difficult to analyze and evaluate the results.
Response: Watershed-scale experiments are inherently difficult to replicate. From the management perspective there are established regulatory thresholds for pesticides and nitrogen in streams and groundwater that the data from our project can be compared to. For sediments, there are a large number of traditional studies that provide a baseline and range for expected sediment losses to streams. Therefore, one metric will be the absolute levels and the second will be the changes (before-after). As the data indicate, the baseline concentrations are currently very low (nitrate, ammonium) or below detection (pesticides).

Question: Short rotation woody biomass is 10-12 years and the project timeline will only go through half that time. A comparison of the water quality to the baseline will be incomplete.
Response: Prior watershed studies in forestry have demonstrated the greatest impact to water quality (sediments, pesticides, N, P) is normally associated with the period from clear cutting through crown closure. Vegetation re-growth mitigates effects with age. Intensification of vegetation control coupled with fertilization in the first 5-6 years is therefore likely to present the greatest potential impact to water quality if BMPs are not adequate.

Question: How common is it to use intensive practices at present day private or large scale production practices?
Response: Chemical site preparation treatments, herbaceous weed control, pre-plant fertilization, and mid-rotation fertilization are all routine operational forestry practices applied to moderately to intensely managed pine plantations across the Southeastern US. Early fertilization is not common, but because the grow gains are compounded, the expectation is that costs and new technology, much like genetic improvement, will enable the landowners to improve nutrition economically in years 1-6 in the near future. Further, the Forest Service has installed pilot-level studies on the same soils at the SRS to understand the utility of these fertilization and herbicide treatments. These studies are several years ahead of our experiment, so we soon will have a better understanding of their potential utility. Regarding the use of improved genetics, the value of tree improvement programs has been well demonstrated and virtually all loblolly pines planted across the Southeast are derived from tree improvement programs.

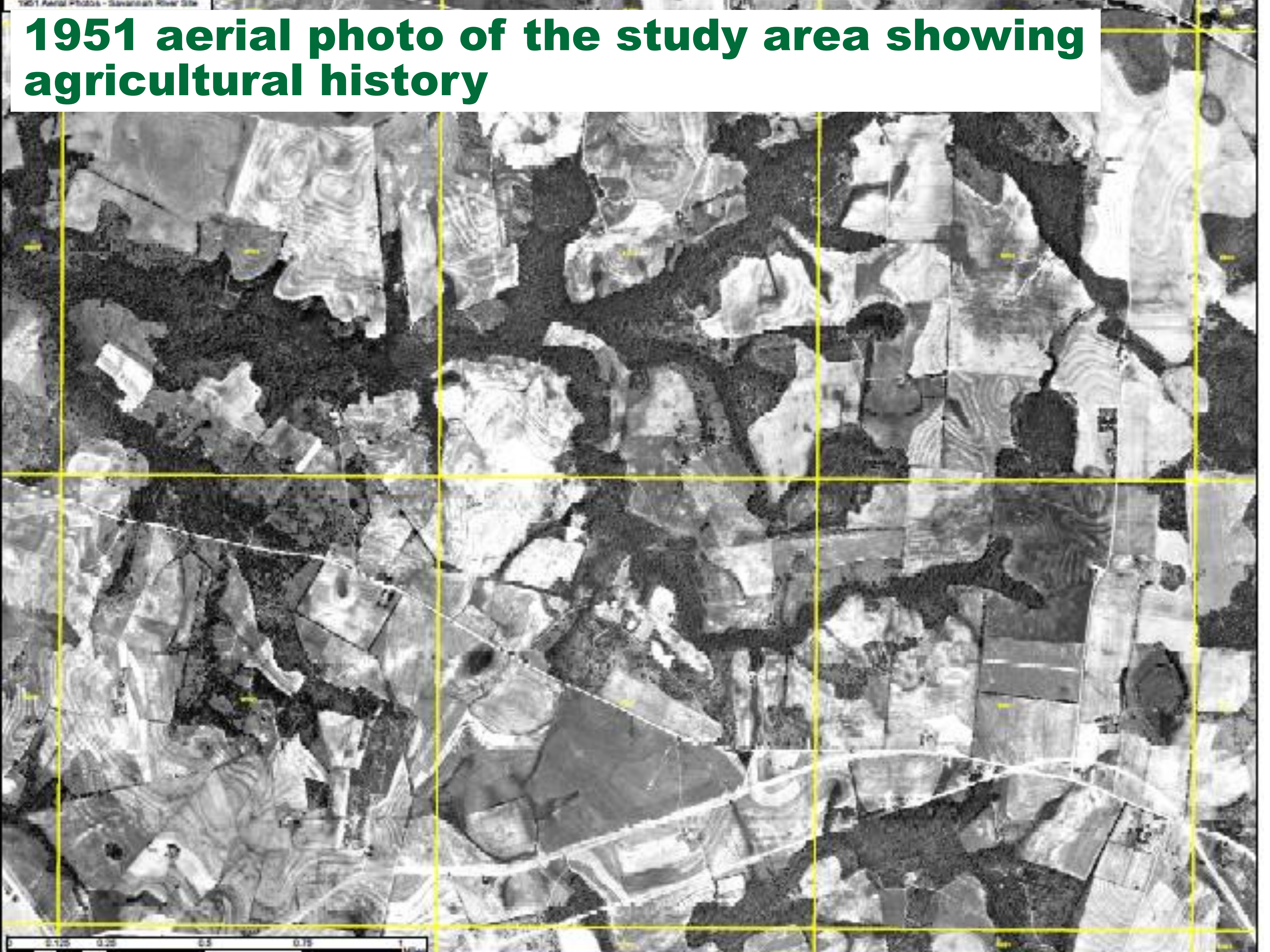
Publications and Presentations (since 2011)

- Williamson, M. 2011. Mesoscale conductivity in argillic layers at the Savannah River Site. MS Thesis, University of Georgia, Athens, GA.
- Drover, D.R. 2011. The effects of digital elevation model resolution on the calculation and prediction of topographic wetness indices. MS Thesis, University of Georgia, Athens, GA.
- Jackson, C.R., K.B. Vache, E. Du, J.J. McDonnell, and J.I. Blake. 2011. Modeling issues in up-scaling field and small watershed biogeochemistry data from biomass production experiments. Ecological Society of America Annual Meeting, August 8-12, Austin, TX. Oral presentation.
- Griffiths, N.A., P.J. Mulholland, C.R. Jackson, and C.T. Garten. 2011. Biogeochemistry of forested watersheds in the Upper Coastal Plain of the Southeastern U.S. prior to conversion to short-rotation pine for bioenergy. Gordon Research Conference in Catchment Sciences, July 11-14, Lewiston, ME. Poster.
- Griffiths, N.A. and C.R. Jackson. 2011. What do we need to learn about global change effects in ecosystem science? Global Change Effects on Aquatic Systems: A symposium inspired by the work of Patrick J. Mulholland, November 5, Oak Ridge, TN.
- Du, E., C.R. Jackson, J. Klaus, and L. Hopp. 2011. Perching and interflow occurrence over a shallow argillic layer in a low relief upper Coastal Plain watershed. American Geophysical Union Conference, December 5-9, San Francisco, CA. Poster.
- Jackson, C.R., K.B. Vache, and E. Du. 2011. Parameter choice and constraint in hydrologic models for evaluating land use change. American Geophysical Union Conference, December 5-9, San Francisco, CA. Poster.
- Klaus, J., K.B. Vache, E. Du, and J.J. McDonnell. 2011. Process representation and uncertainty reduction for modeling the effects of bioenergy crop systems on catchment-scale water use. American Geophysical Union Conference, December 5-9, San Francisco, CA. Poster.
- Jackson, C.R., E. Du, J. Klaus, N.A. Griffiths, J.J. McDonnell, and J.I. Blake. 2012. Whole hillslope irrigation reveals differential interflow behavior of dye tracers, conservative solutes and nutrients. American Geophysical Union Conference, December 3-7, San Francisco, CA. Poster.
- Du, E, C.R. Jackson, and M.F. Wiliamson. 2012. Effects of measurement scale on saturated hydraulic conductivity estimates in loamy sand and argillic soils: from point to hillslope. American Geophysical Union Conference, December 3-7, San Francisco, CA. Poster.
- Du, E., C.R. Jackson, J.I. Blake, N.A. Griffiths, J. Klaus, J.J. McDonnell, K.B. Vache, and M.H. Langholtz. 2012. Modeling water quality within biofuel production landscapes: integrating hillslope flow paths, deep groundwater dynamics, riparian groundwater interactions, and end-member chemistry. American Geophysical Union Conference, December 3-7, San Francisco, CA. Poster.
- Klaus, J., J.J. McDonnell, E. Du, C.R. Jackson. 2012. Quantifying catchment water cycle connections via the local meteoric and evaporation water lines. American Geophysical Union Conference, December 3-7, San Francisco, CA. Poster.
- Griffiths, N.A., P.J. Mulholland, C.R. Jackson, J.J. McDonnell, J.I. Blake, E. Du, J. Klaus, and M.H. Langholtz. 2012. Biogeochemistry of forested watersheds in the Southeastern U.S. prior to the conversion to short-rotation pine for bioenergy. American Geophysical Union Conference, December 3-7, San Francisco, CA. Poster.

Abbreviations

AGM MCP 37 – Loblolly pine seedling family
BETO – Bioenergy Technologies Office
BMPs – Best Management Practices
DOE – Department of Energy
EERE – Energy Efficiency and Renewable Energy
EPA – Environmental Protection Agency
ET – Evapotranspiration
Fourmile – Larger watershed where 3 study watersheds drain to
MYPP – Multi-Year Program Plan
^{15}N – Stable isotope of nitrogen (used to measure nitrate cycling through the watersheds)
NCASI – National Council for Air and Stream Improvement
NH_4 – Ammonium
NO_3 – Nitrate
^{18}O – Stable isotope of oxygen (used to measure water and nitrate cycling)
Op. – Operational
ORNL – Oak Ridge National Laboratory
OSU – Oregon State University
S.E. – Southeast(ern)
SRP – Soluble reactive phosphorus
SRS – Savannah River Site
TP – Total phosphorus
UGA – University of Georgia
US – University of Saskatchewan
USFS-SR – United States Forest Service – Savannah River
Watersheds B and C – Treatment watersheds (locations of clear cuts)
Watershed R – Reference watershed

1951 aerial photo of the study area showing agricultural history

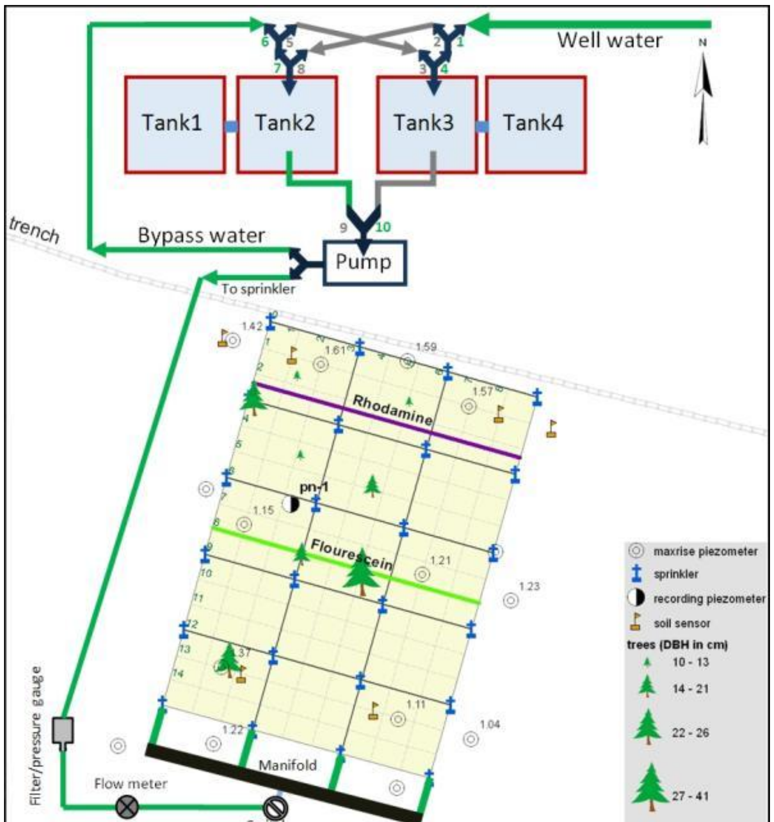


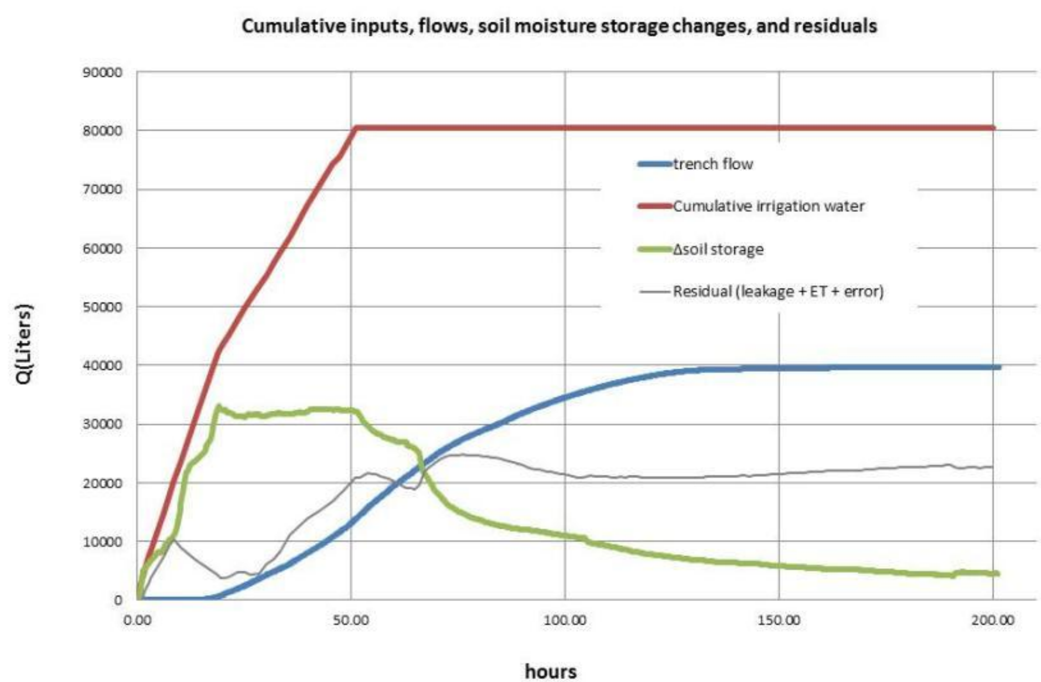
Typical regenerated pine stand and hillslope in study area

Loamy sand topsoil over sandy clay loam argillic layer, typical soil profile of study area hillslopes.

Irrigation experiment

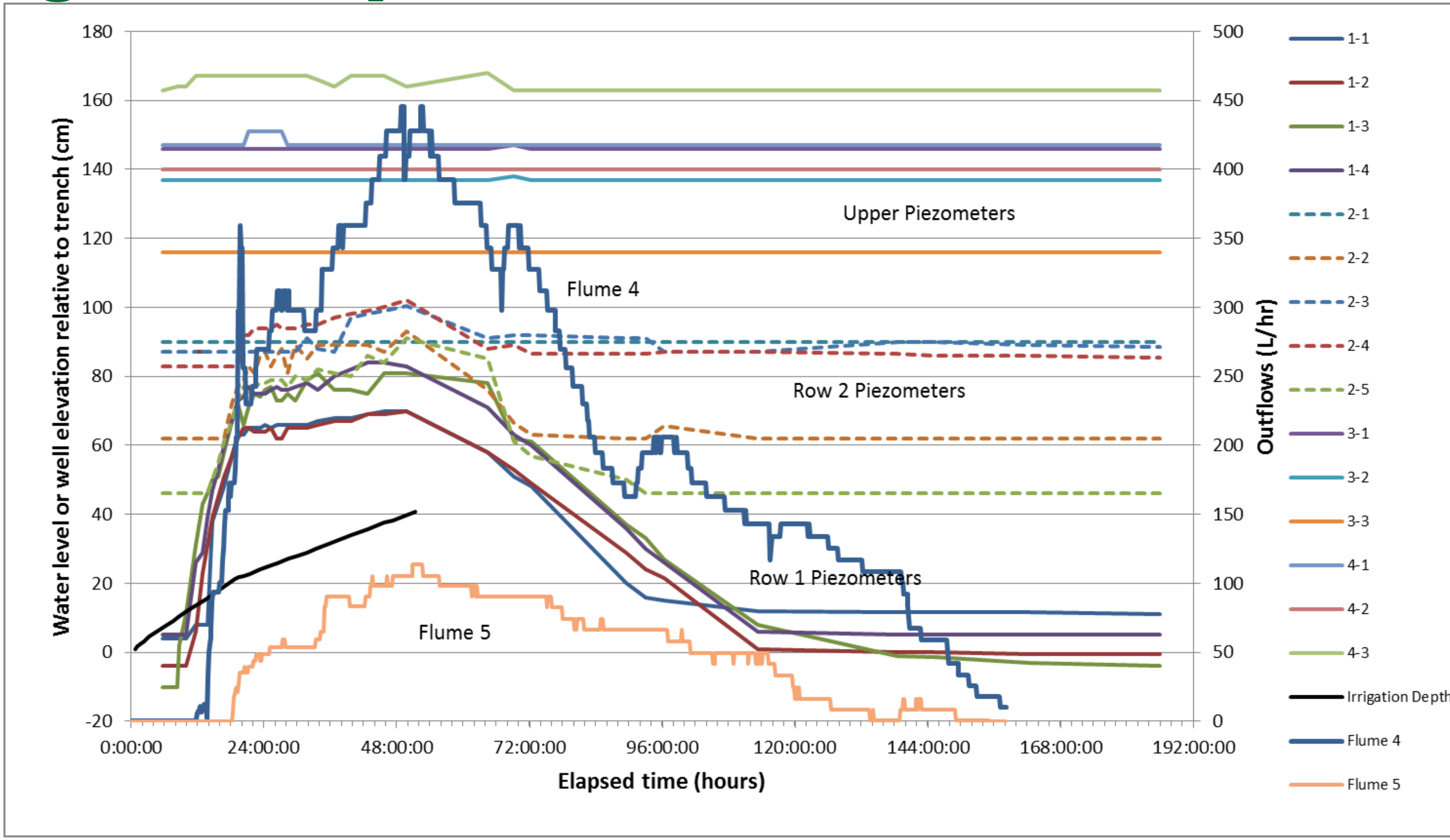
40.7 cm of water was applied, 49% (19.9 cm) appeared as trenchflow. 64% (12.8 cm) of the trenchflow was "old" water according to isotope fractions. To produce this much old water, the new water had to displace water that was previously held very close to the soil particles (water previously held below wilting point). Some water must have moved through the clay since the sand couldn't produce that much water and diffusion couldn't exchange that much water in this time frame.





49% of applied water eventually appeared as interflow intercepted by the trench.

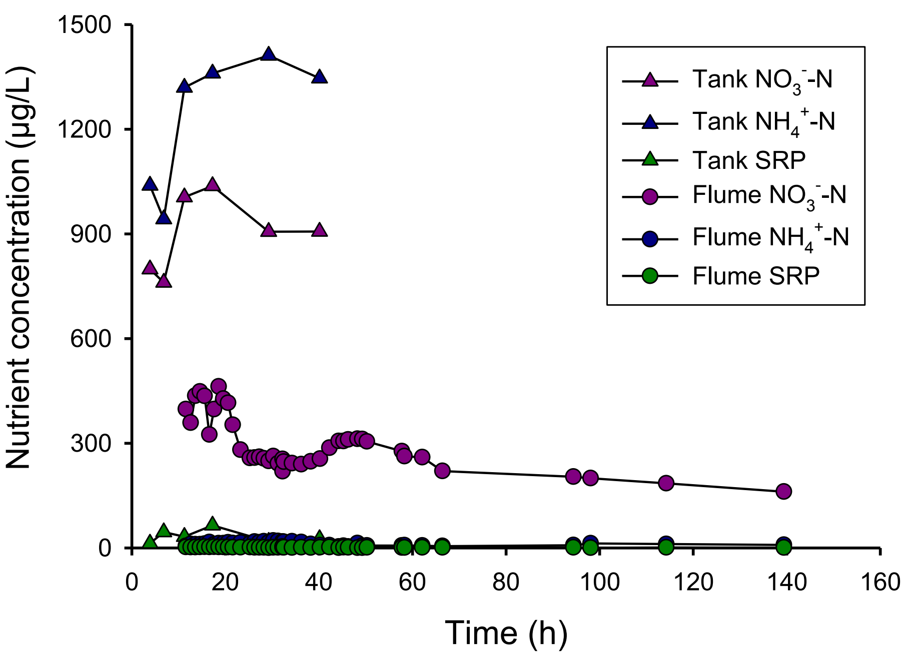
Irrigation experiment results

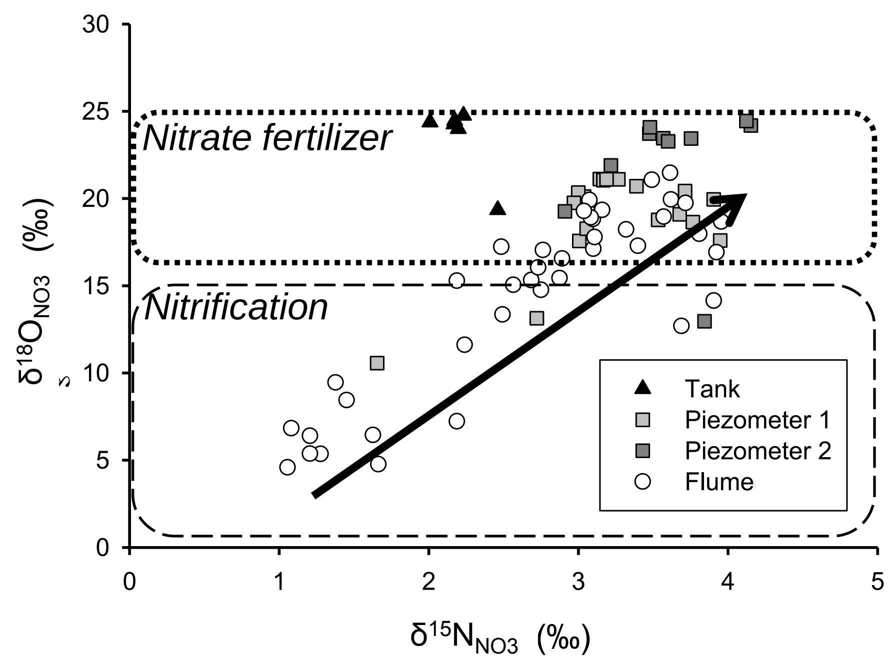


Trench flow initiated at 13.1cm (flume 4) and 17.8cm (flume 5) of irrigation. This verifies the high threshold for initiation of interflow that previous slope observations had suggested. Trench flow continued for 100 hours (4.2 days) following cessation of irrigation. Perching continued from 60 hours (2.5 days) to over 130 hours (5.4 days) depending on position. The saturated wedge extended only halfway up the irrigated slope - flow from the upper slope was unsaturated or moving through the clay.

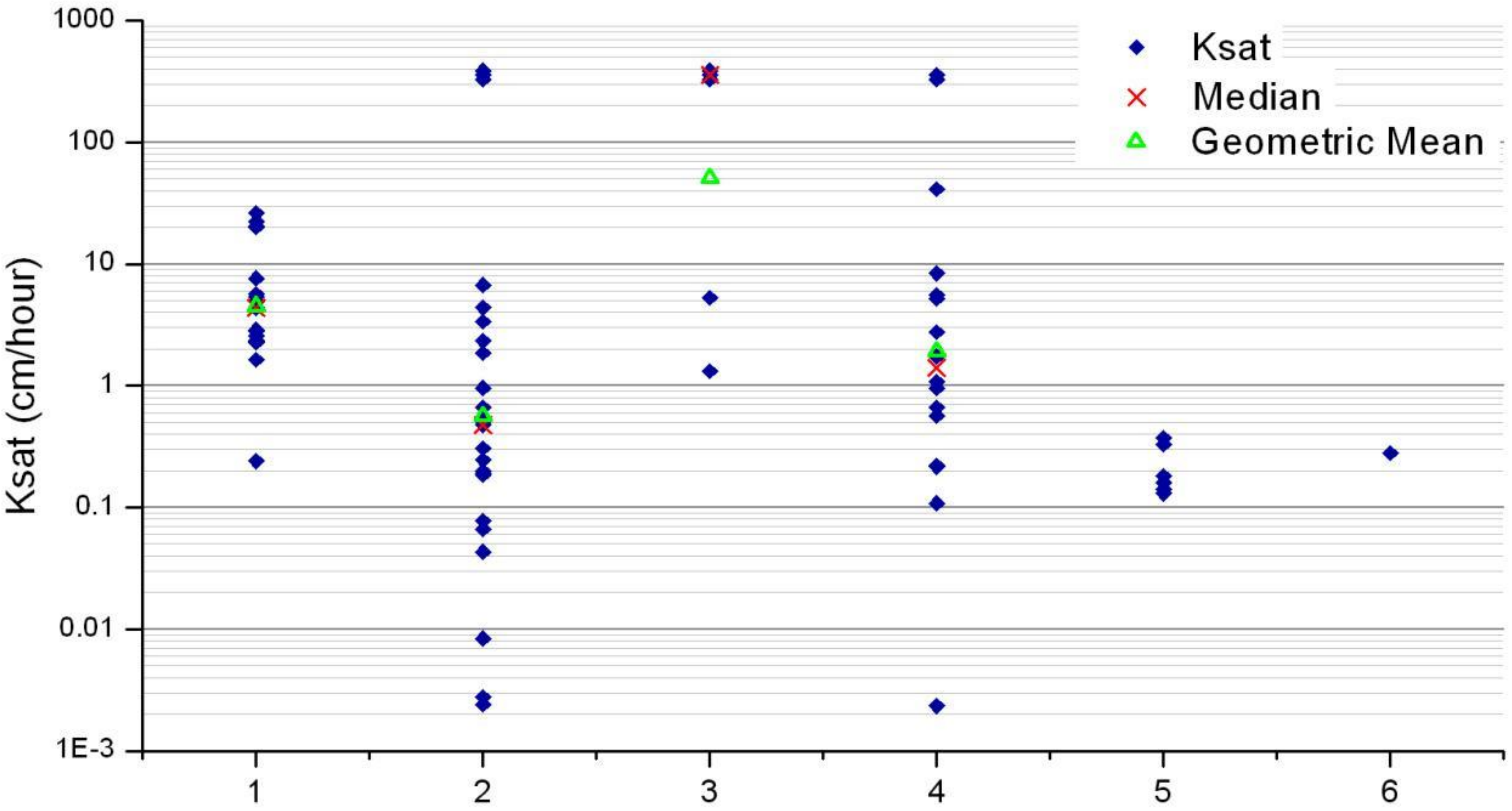
Nutrient behavior during irrigation expt.

- Nitrogen and phosphorus addition experiment showed that when nutrients are applied on a hillslope (i.e., fertilizers), nitrate is mobile while ammonium and phosphate are taken up by biota and/or adsorbed by clay-rich soils.
- Nitrate applied on the hillslope was measureable in the trench flow water (more enriched ^{18}O and ^{15}N of nitrate, as shown with the directional arrow).
- Field observations and the nutrient addition during the irrigation experiment suggest that nitrate may end up in groundwater rather than flowing from the hillslope directly to the stream





Hydraulic conductivities of the argillic layer are highly variable when measured at the small scale, but the variance collapses when measured at the one meter scale (large infiltrometers) as confirmed by the irrigation experiment.

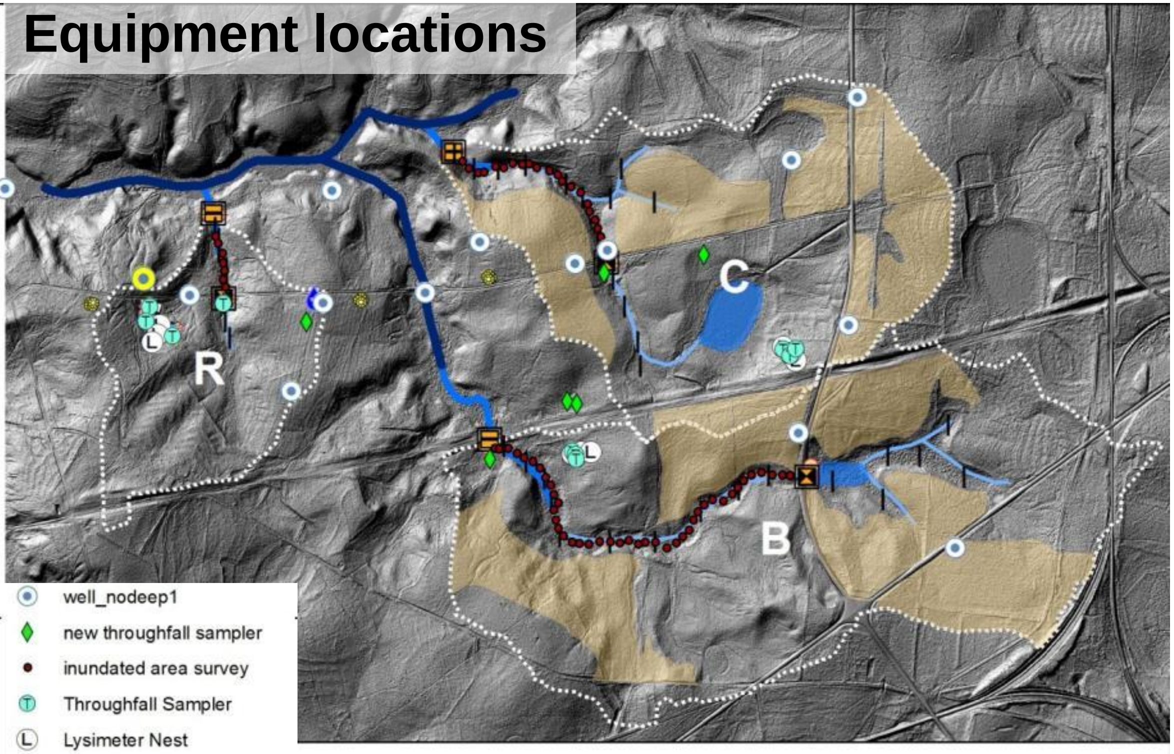


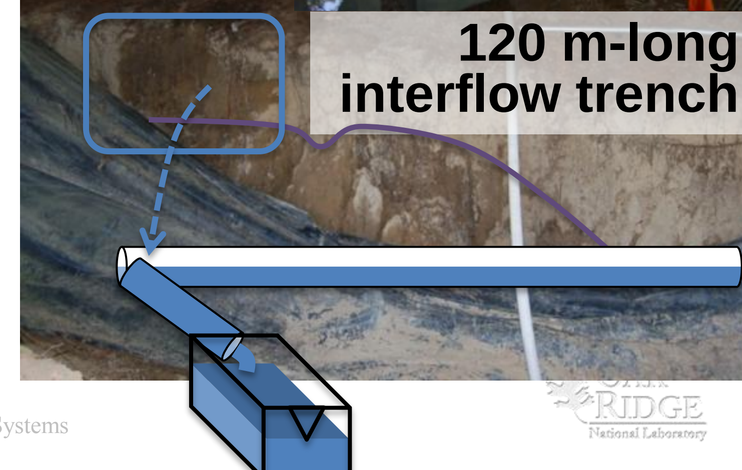
1 = A and E horizons, 2 = randomly selected argillic horizon, 3 = Argillic visual anomaly (measured in trench cut into the argillic), 4 = GPR identified anomaly, 5 = Large infiltrometer, 6 = sprinkler experiment

Typical stream valley. Each watershed includes an intermittent stream and long, flat valleys with indistinct channels characteristic of the SE Coastal Plain (photo of Watershed B).

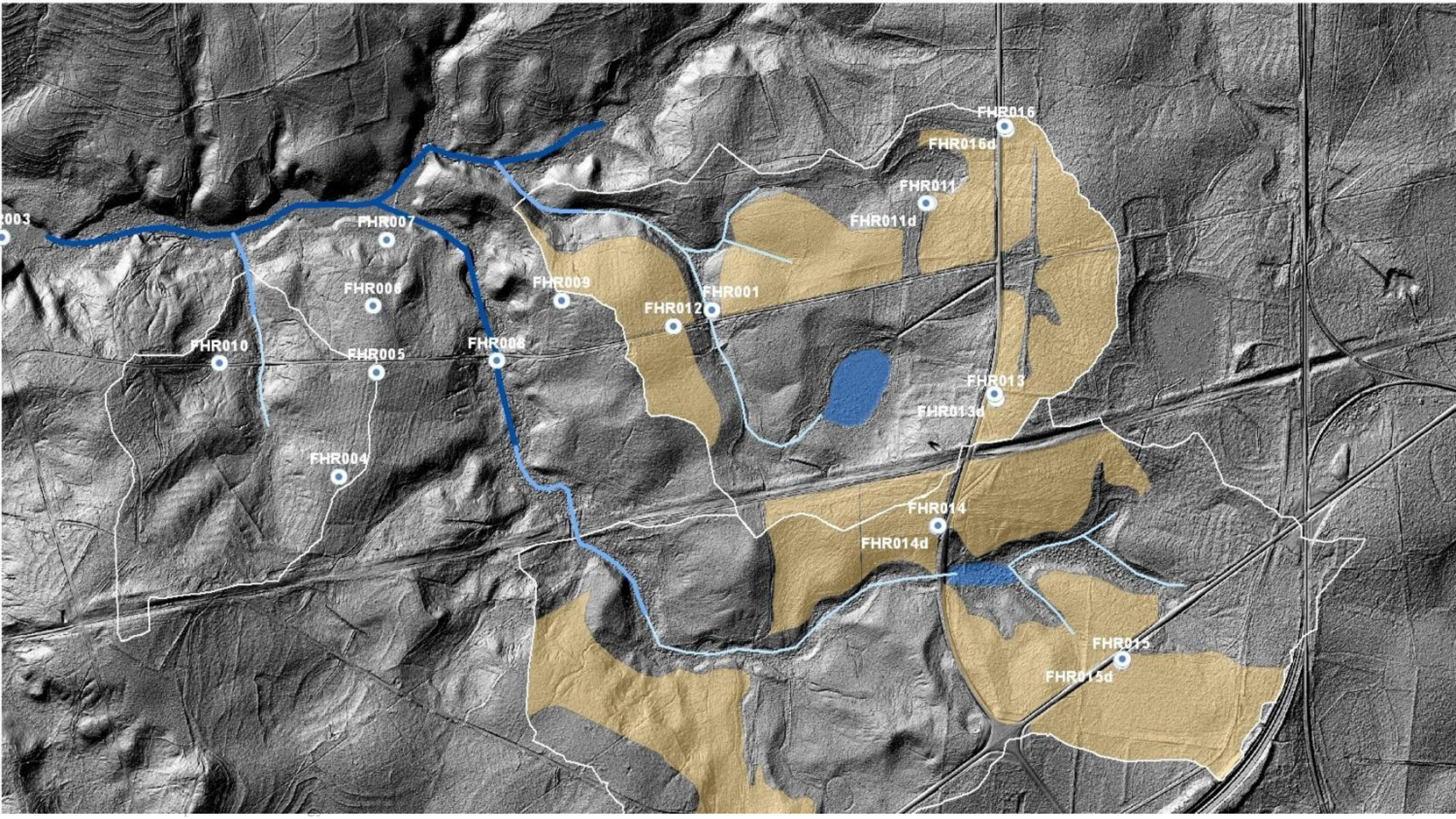
Open interflow interception trench on reference watershed hillslope

Watershed monitoring system and infrastructure

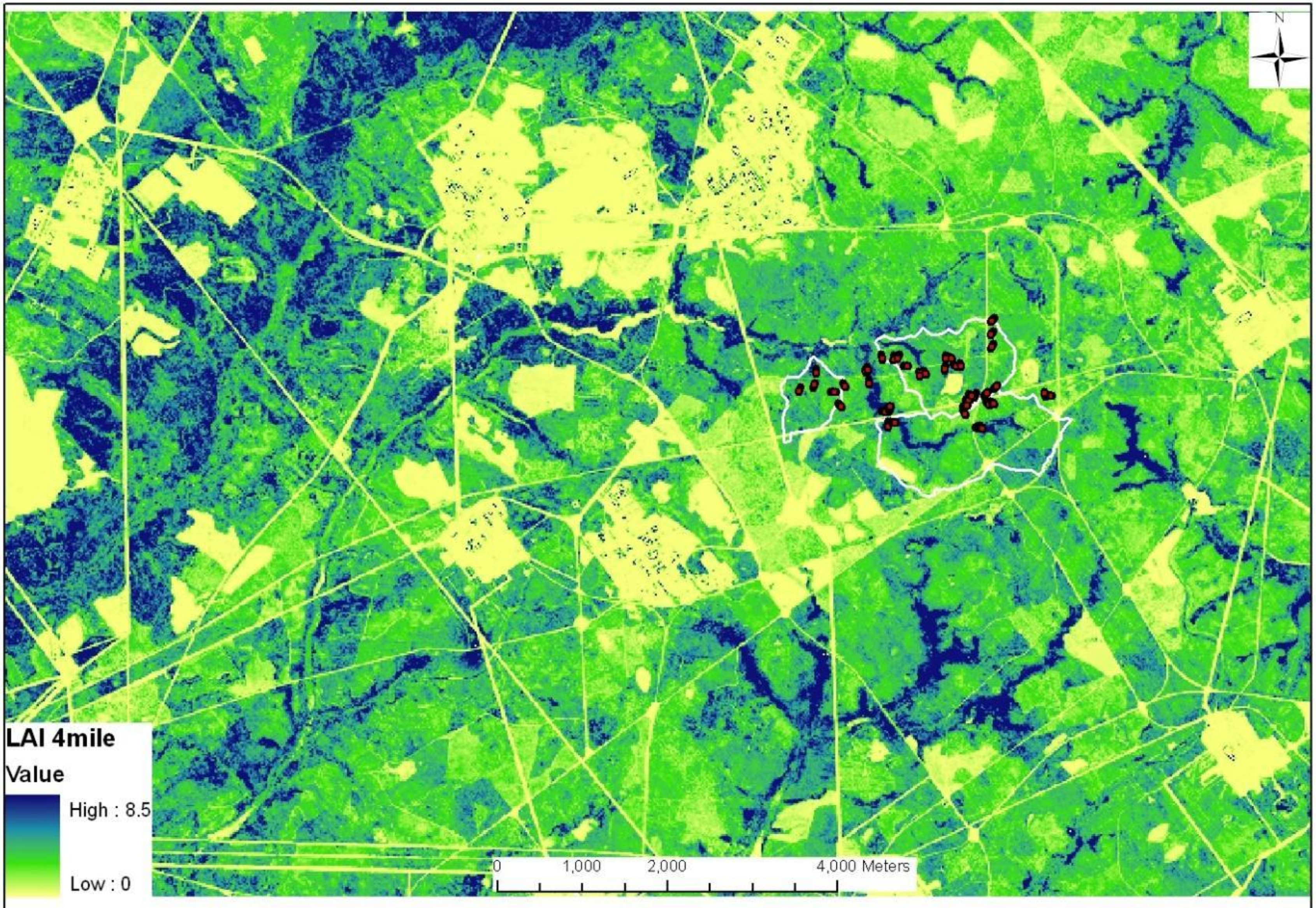




Locations of deep groundwater wells with respect to watersheds and harvest areas. Several locations have a well pair – one deeper and one shallower.



Leaf area index (LAI) map of Upper Fourmile Basin created with LiDAR data informed by spot LICOR LAI measurements (red dots).



Timber harvest (March – May 2012)

Clear cut area with riparian zone intact

Site preparation/ripping rows for planting (June – September 2012)

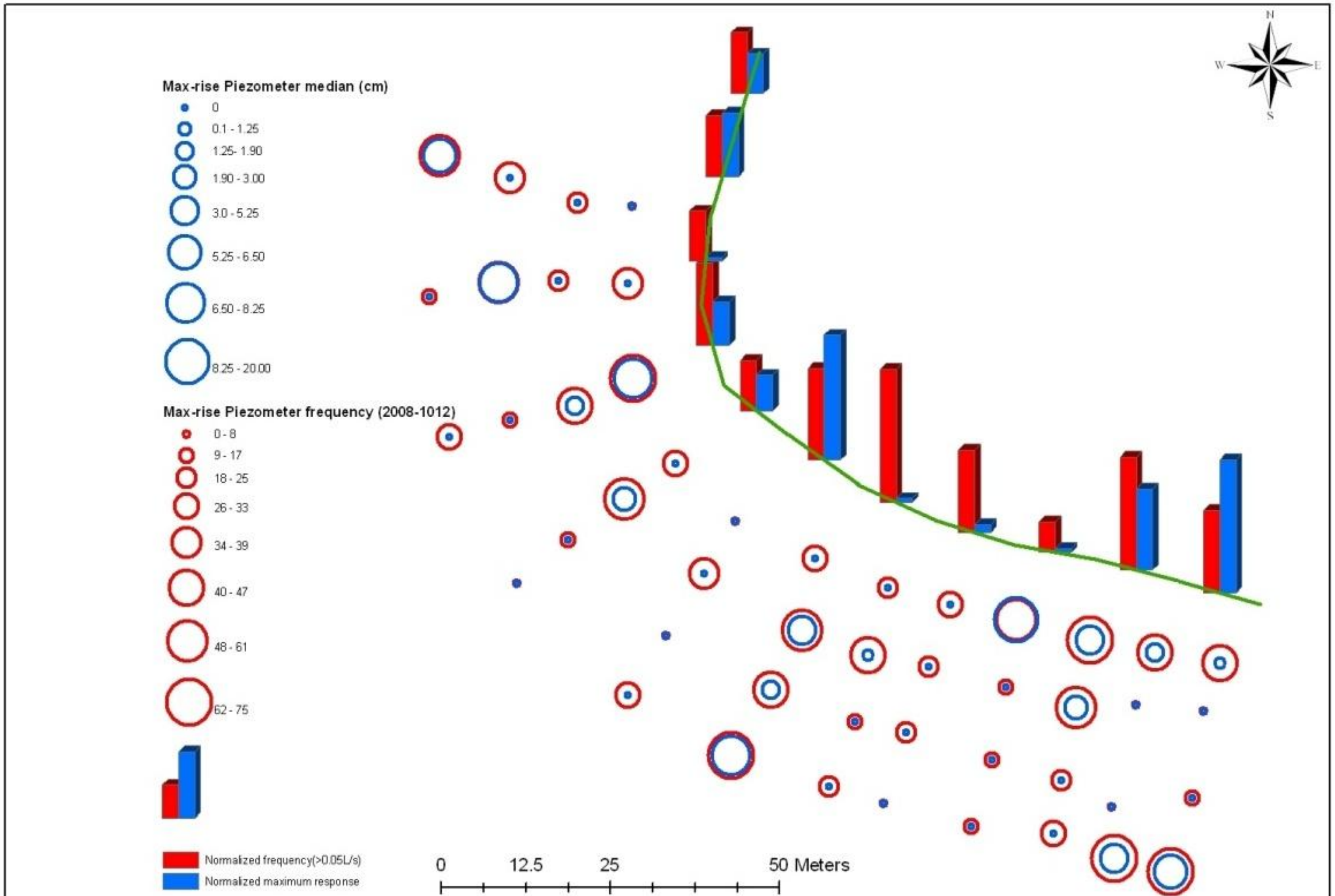
Herbicide application (September 2012 and March 2013)

Loblolly pine seedlings (planted Jan – Feb 2013)

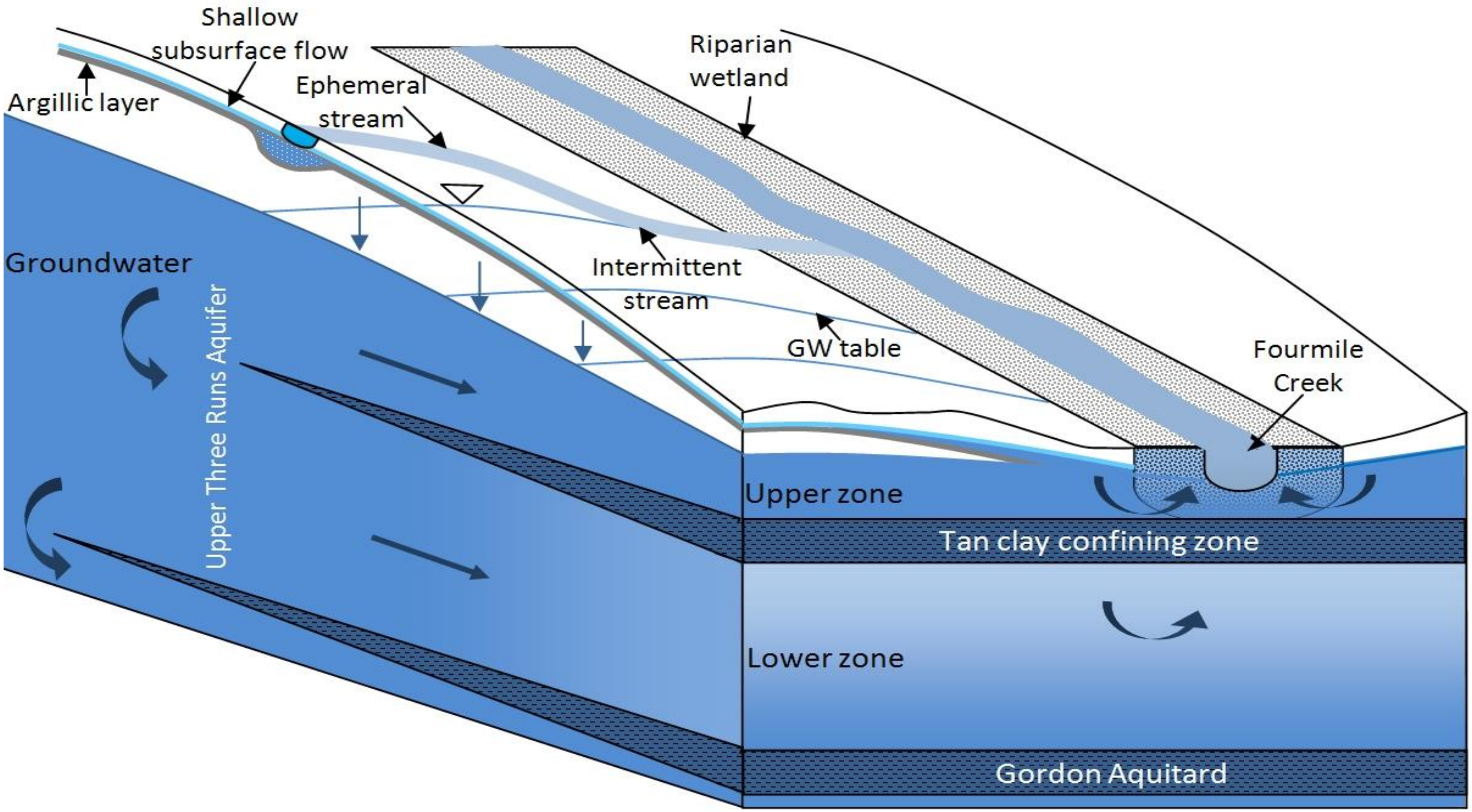
Loblolly pine seedlings and N cycling plot (no herbicide addition treatment)

On the sandy soils of the Upper Coastal Plain at SRS, all observed overland flow reinfiltrates in the first few meters of the streamside management zone (SMZ). Overland flow does not connect to streams.

Perching of shallow water over the argillic clay layer and interflow production are highly spatially variable. Results below are from the 120m interflow interception trench in the R watershed.



Most storm water falling on the upslope percolates through the argillic layer and enters the regional groundwater reservoir. The first-order streams are fed largely by water perched on clay layers below the riparian zone. Regional groundwater is intercepted in higher order streams (e.g., Fourmile Creek).



Impact of weed control, fertilization, and advanced genetics for woody crops from 7 studies in the Southeastern U.S.

S.E . U.S. Pine Study	Stand Age	Yield (tons/ac/yr)
GA 1	12	13.6
GA 2	12	11.4
GA 3	10	9.9
GA 4	11	9.7
GA 5	11	9.7
GA 6	11	11.2
SC-SRS	10	10.6
Conventional	10	2 to 3