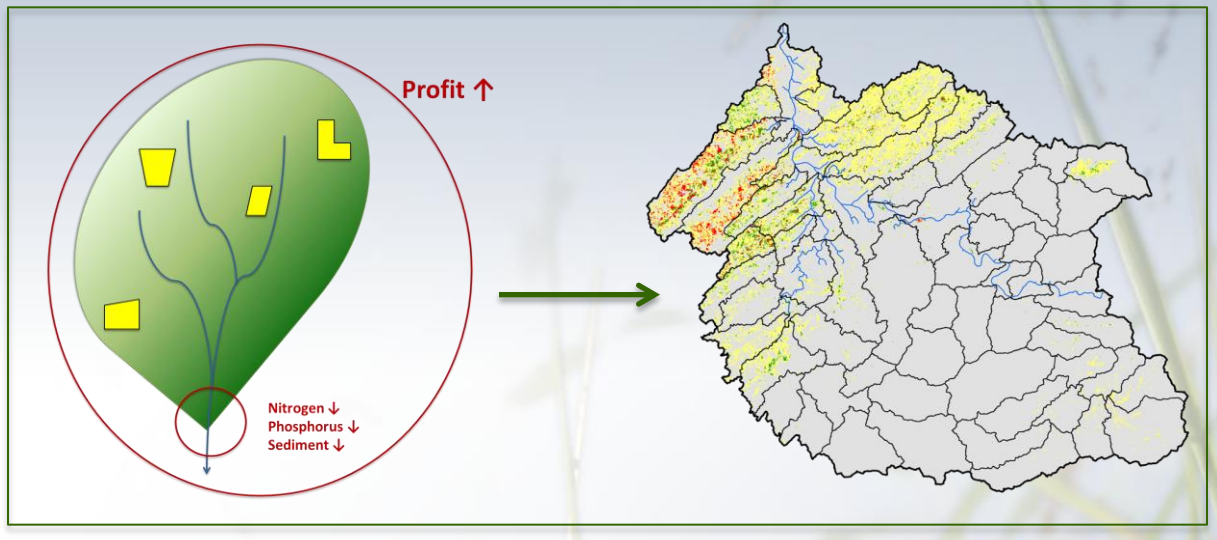
CBES
Center for BioEnergy Sustainability



MULTIMETRIC SPATIAL OPTIMIZATION OF BIOENERGY CROPS ACROSS A WATERSHED

Esther S. Parish
Environmental Sciences Division
Oak Ridge National Laboratory

Billion Ton Study Workshop:
What can be Learned about Bioenergy Sustainability?
Oak Ridge National Laboratory

September 30, 2011

U.S. DEPARTMENT OF ENERGY

OAK RIDGE National Laboratory

Talk Overview

1. Theoretical framework of landscape design for sustainability
2. Design of the Biomass Location for Optimal Sustainability Model (BLOSM) to include data & assumptions developed for BTS
3. Application of BLOSM research tool to the Lower Little Tennessee (LLT) Watershed
4. Results obtained from 6 scenarios
5. Next steps

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Our Interdisciplinary Biomass Location for Optimal Sustainability (BLOSM) Team

Virginia Dale (ORNL CBES Director)

Landscape ecology, Bioenergy sustainability, Mathematics

Esther Parish (ORNL ESD)

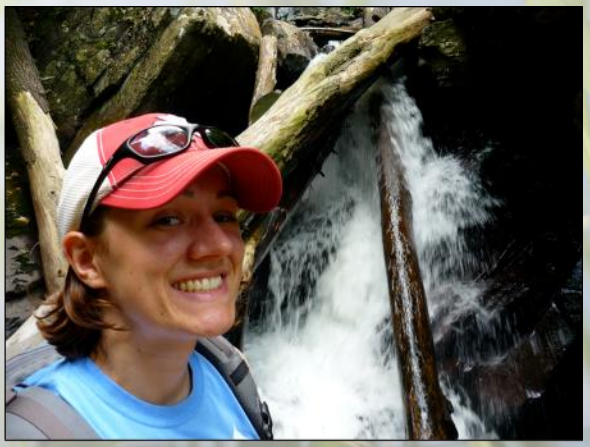
Physical geography, GIS Analysis, Watershed science

Michael Hilliard (ORNL CTA)

Logistics & optimization modeling

Latha Baskaran (ORNL ESD)

Hydrological modeling with SWAT



Natalie Griffiths (ORNL ESD)

Bioenergy impacts on aquatic & terrestrial biogeochemistry

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Our Interdisciplinary BLOSM Team (continued)

Patrick Mulholland (ORNL ESD)
Aquatic biogeochemistry

Alexandre Sorokine (ORNL CSED)
Parallel processing of geographic data

Mark Downing (ORNL ESD)
Agricultural economics

Richard Middleton (LANL)
Energy infrastructure modeling

Neil Thomas (ORNL CTA)
Software design, web interface

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Other folks helped too!

- Robin Graham
- Laurence Eaton
- Amy Wolfe
- And especially our UT collaborators:
  - Sam Jackson
  - Tim Rials

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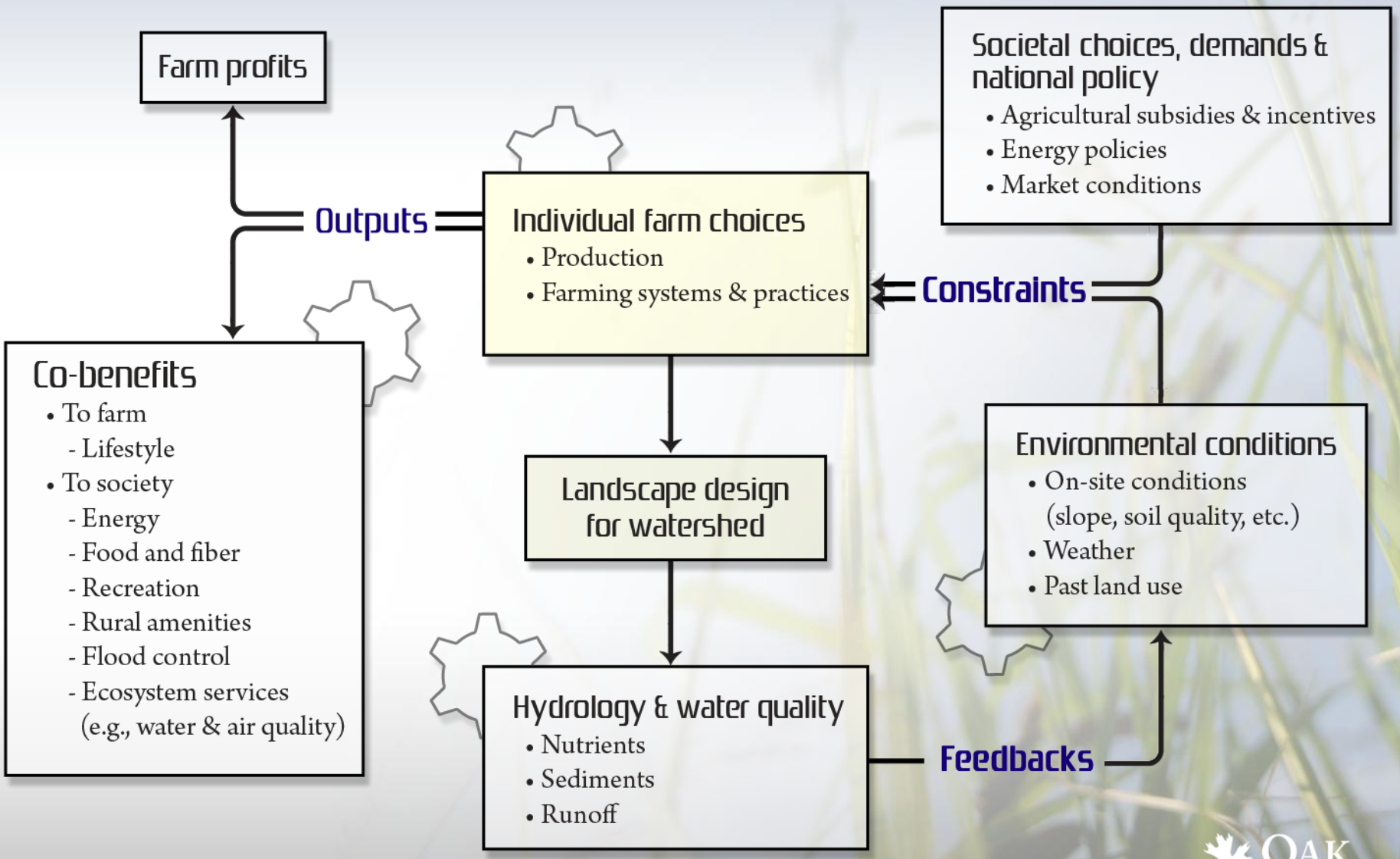
The Effects of Bioenergy Choices *(Conceptual Diagram)*



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A watershed approach to landscape design

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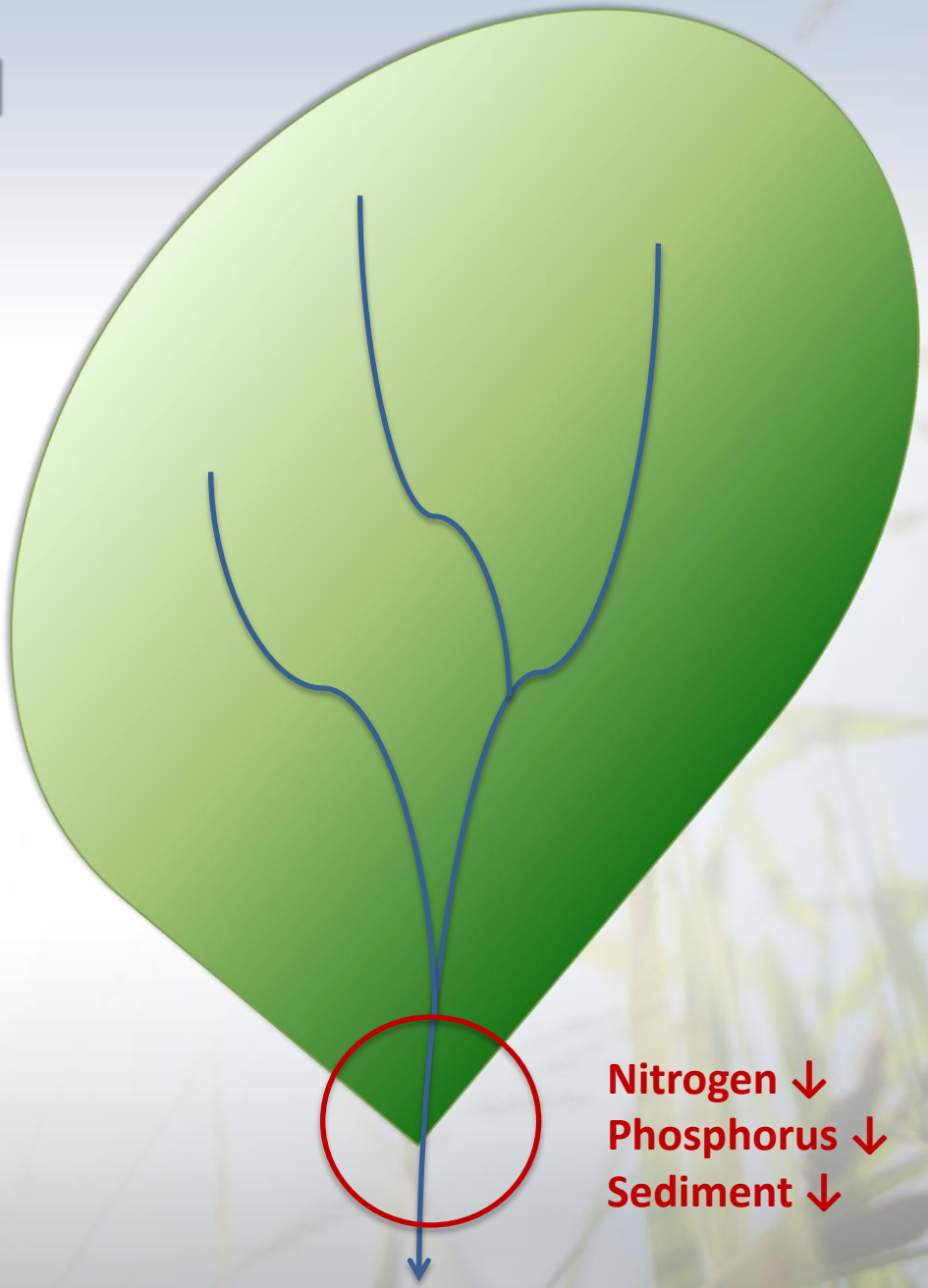
A watershed approach to landscape design



Nitrogen ↓
Phosphorus ↓
Sediment ↓

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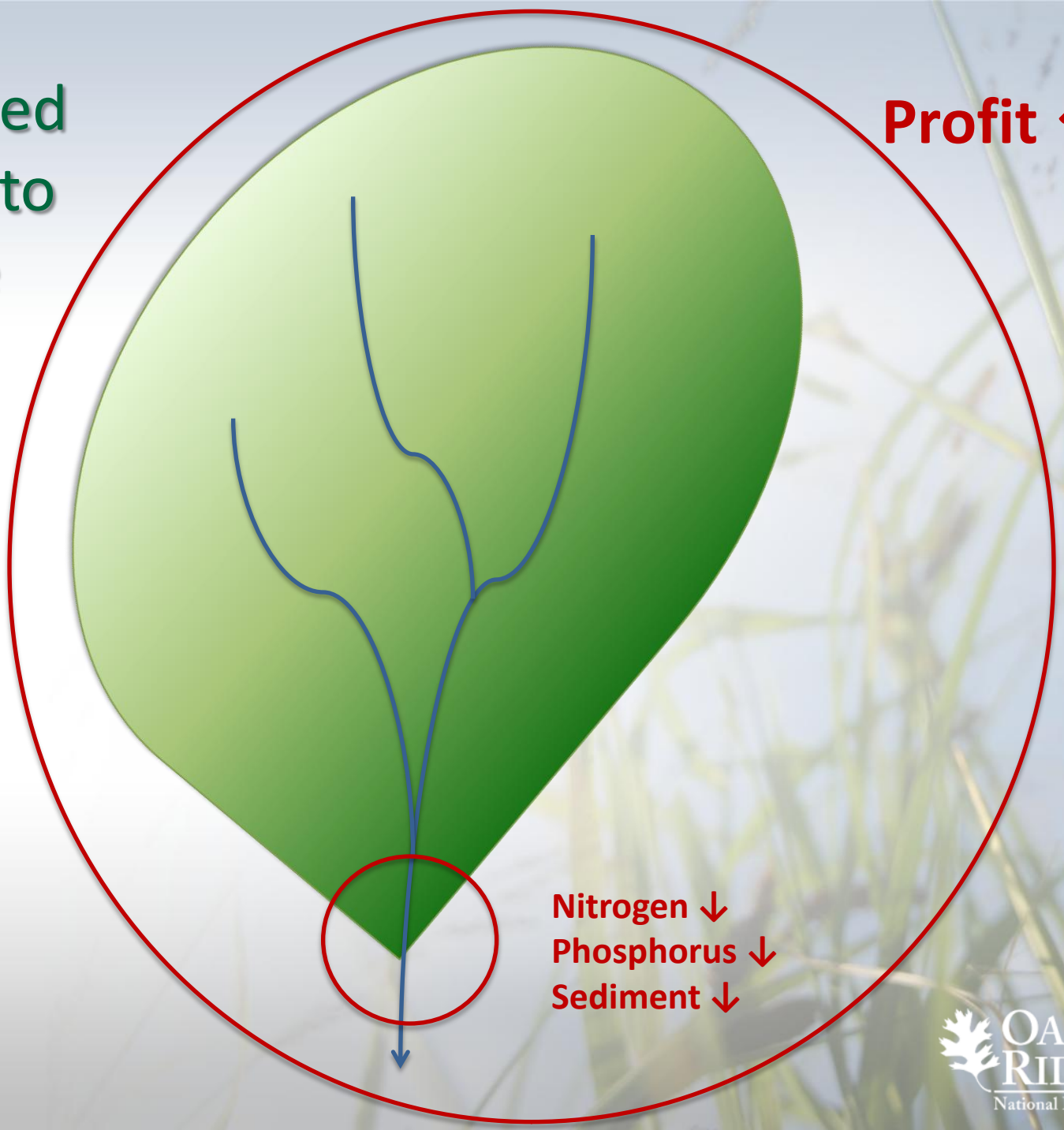
A watershed approach to landscape design



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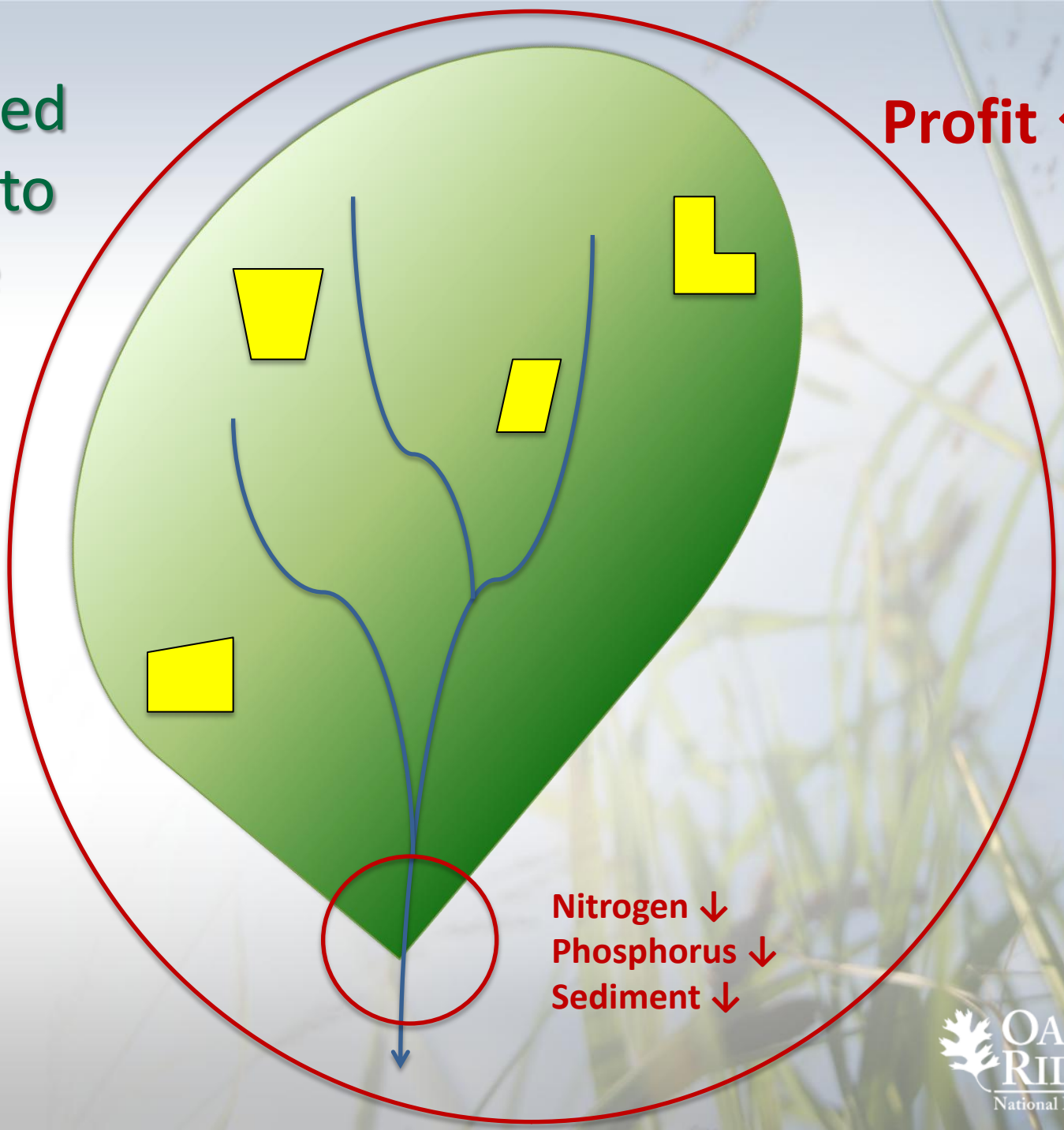
A watershed approach to landscape design

Which crop configuration maximizes sustainability objectives while achieving target production?



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Case Study:
Lower Little Tennessee Watershed

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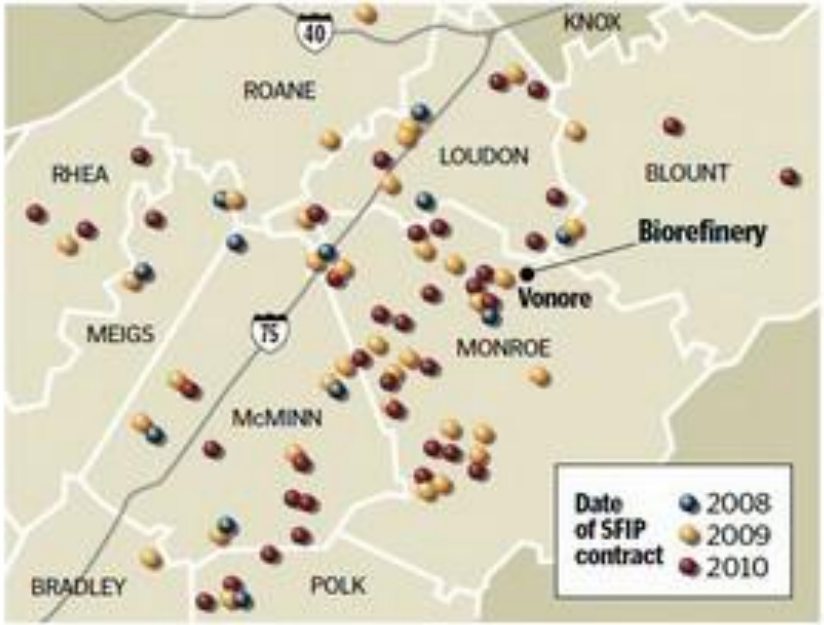
Cellulosic ethanol production is underway in East Tennessee



County	Total acres	Farmers
Monroe	2,205.3	26
McMinn	818.1	10
Loudon	553.9	6
Blount	469.5	4
Bradley	354.7	2
Polk	291.9	3
Rhea	258.1	5
Roane	118.8	4
Hamilton	58.6	1
Meigs	33.3	2
Totals	**5,162.2**	**63**

Year	New farmers	Total production in tons
2008	16	1,000
2009	24	6,000
2010	21	*15,000

*Estimated

Farmer type	Farmers
Full time	31
Part time	30

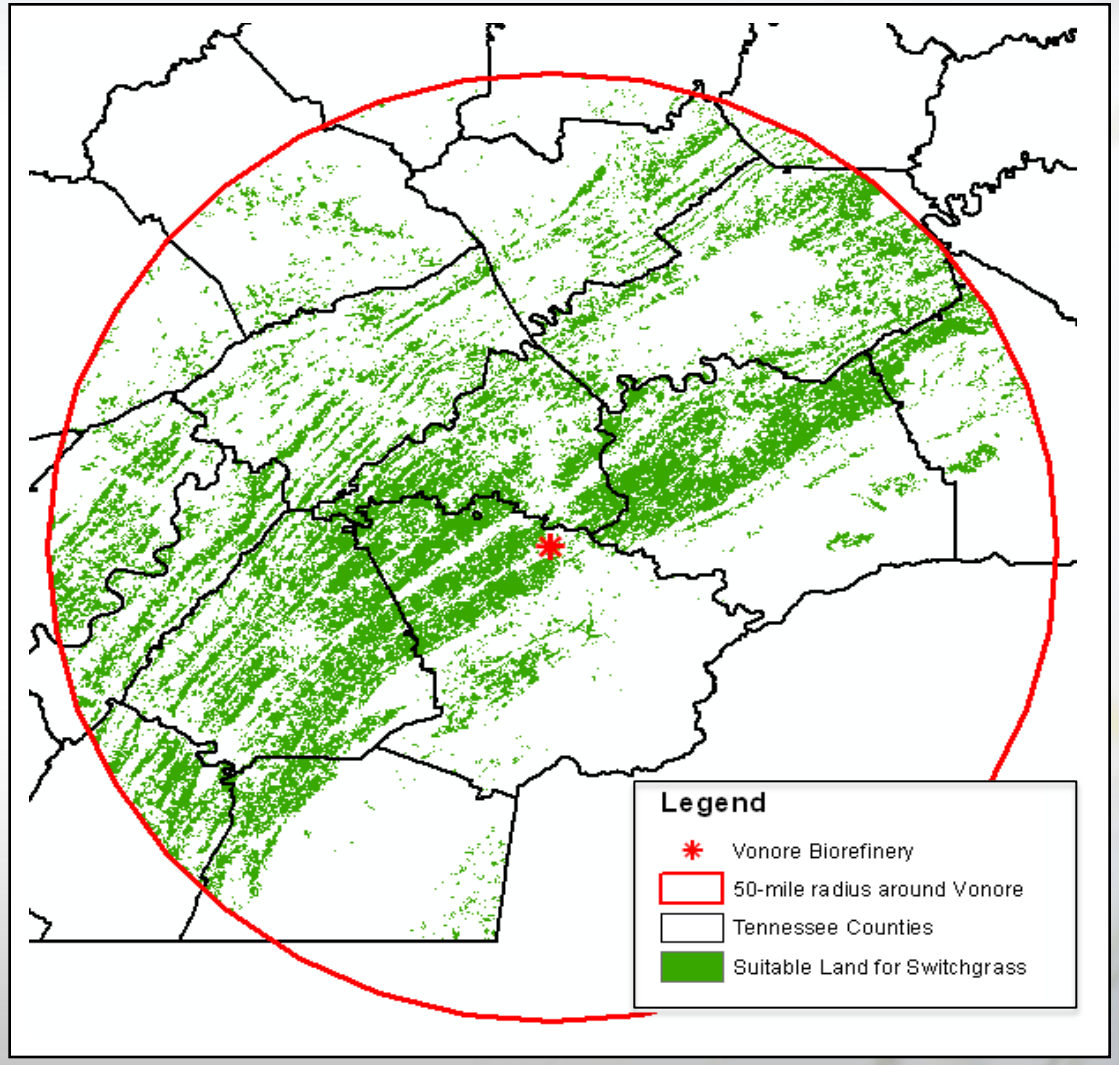
Source: Genera Energy LLC

NEWS SENTINEL

Vonore, Tennessee, USA demo-scale biorefinery (250Mgal/yr) & nearby switchgrass bales

Photos from Genera Energy LLC

ORNL prepared a GIS tool to help incorporate landscape design into selection of new switchgrass locations



This tool synthesized important watershed & site characteristics, including:

- slope
- current land cover
- land use history
- total % impervious cover
- soil type
- stream type
- riparian zones
- proximity to impaired streams
- proximity to existing stream gages
- road access

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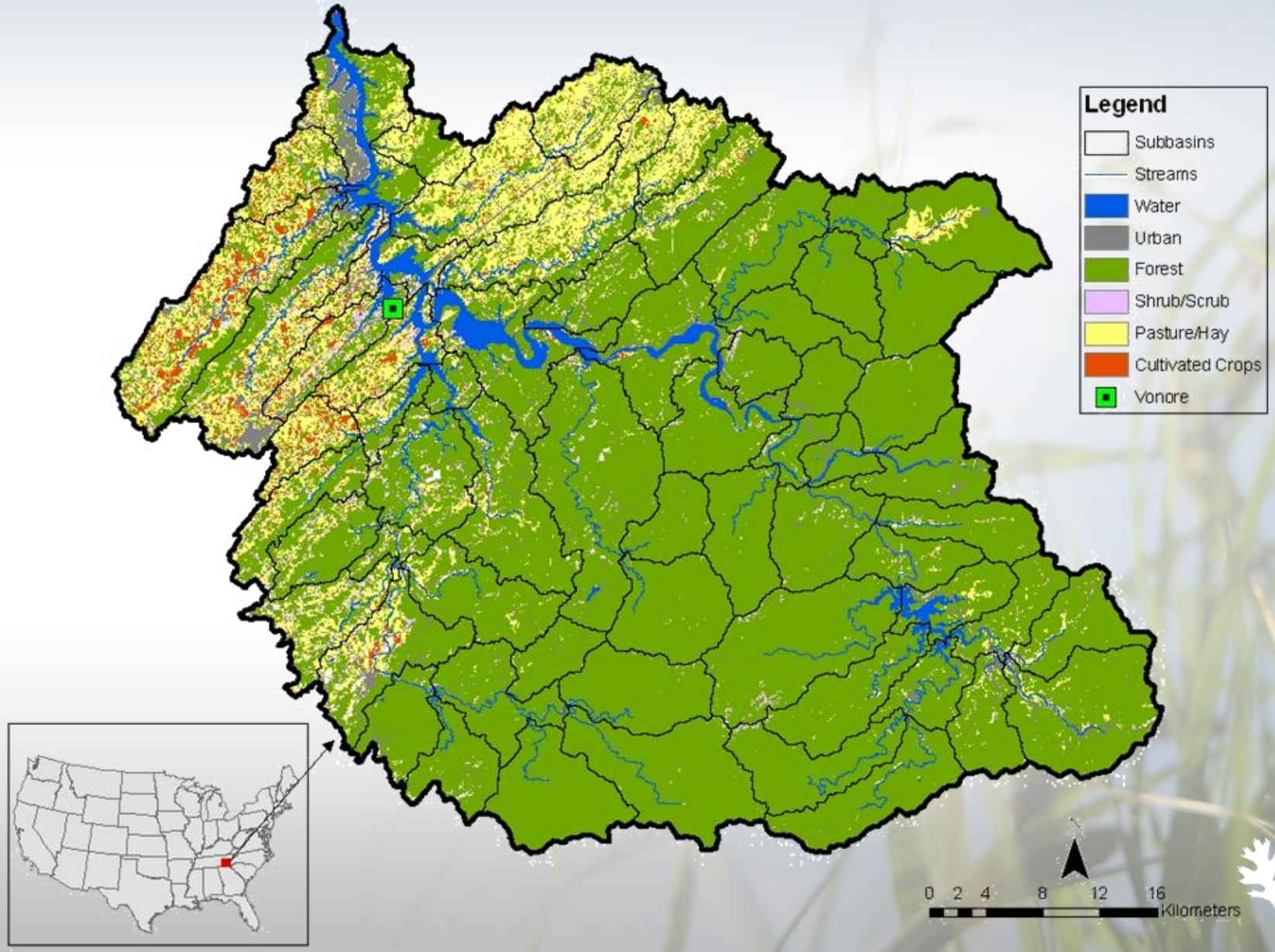
The Lower Little Tennessee (LLT) Watershed (straddles 2 states; includes 6 counties)



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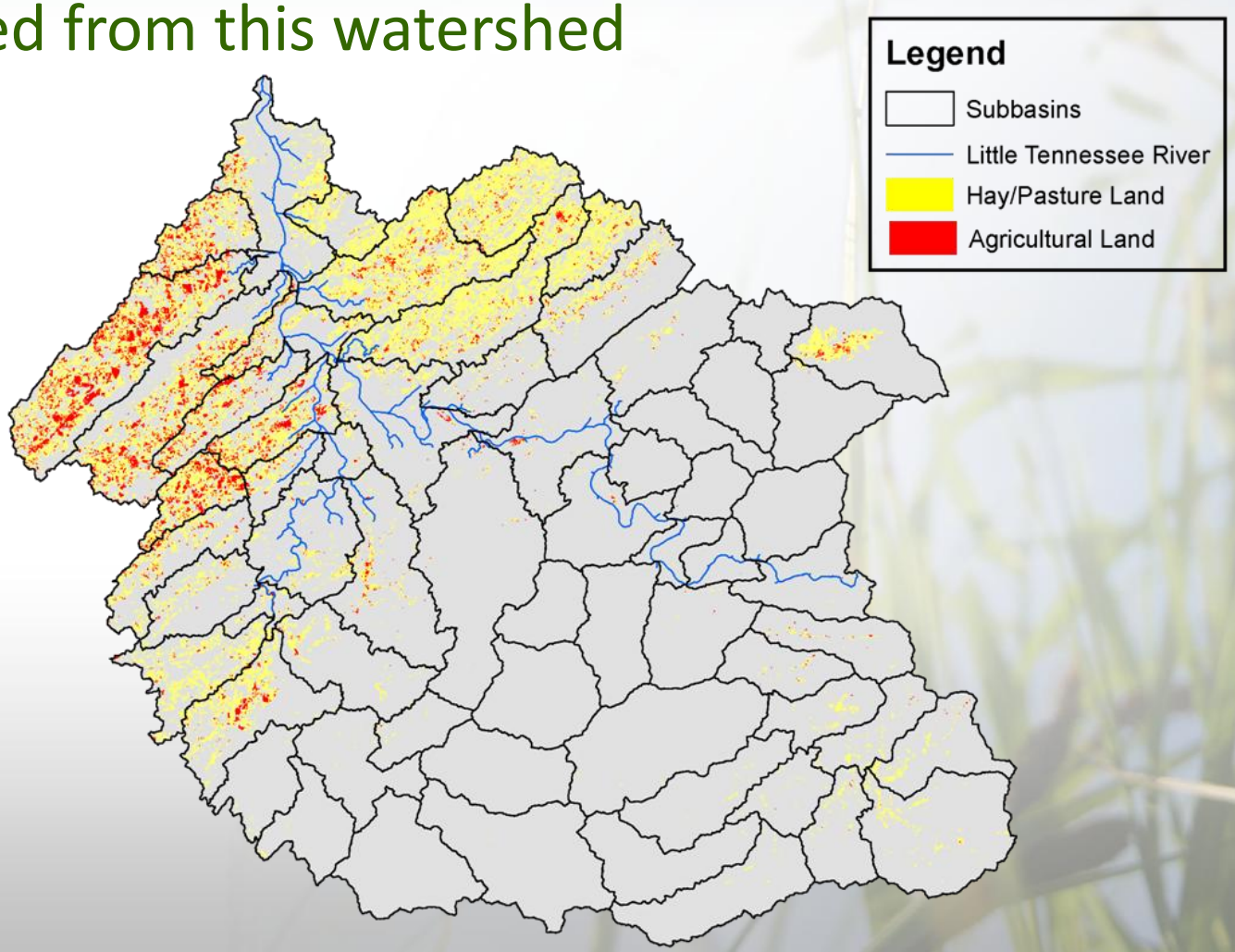
- Only current “pasture/hayland” and “agricultural” land (assumed to be corn) was considered for conversion
- Estimated that 65,000 tons/year of switchgrass might be needed from this watershed



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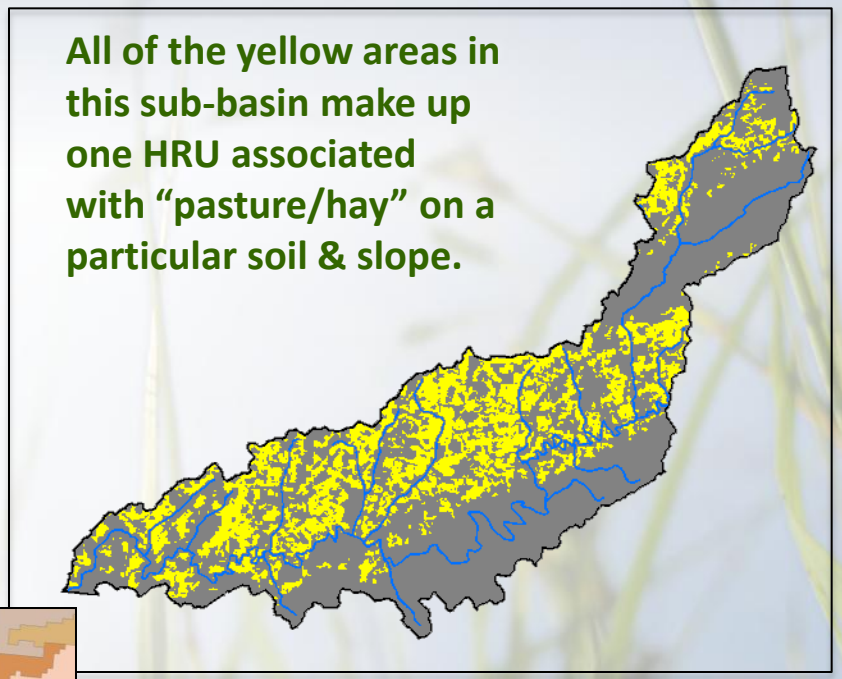
BLOSM's land conversion units = Hydrologic Response Units (HRUs)

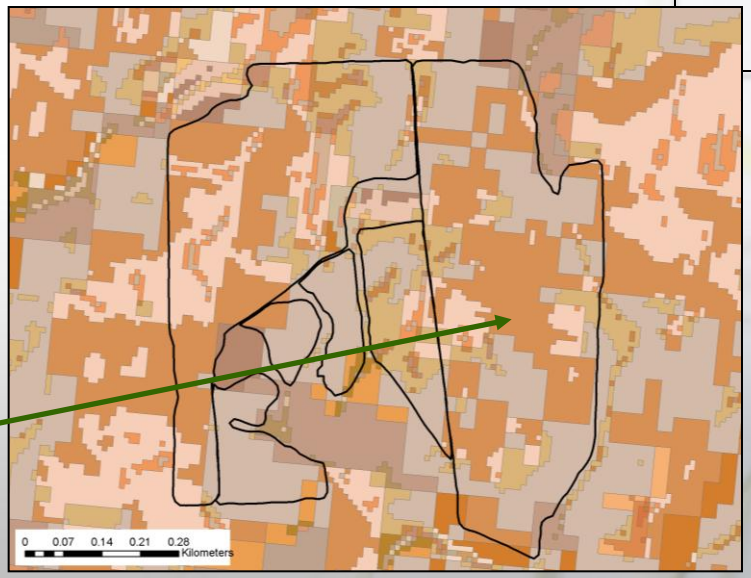
The Soil Water Assessment Tool (SWAT) creates HRUs within each sub-basin based on a particular combination of:

- land use
- soil type
- slope category

HRUs are collections of related polygons rather than contiguous land areas



57-acre field formerly planted in corn



Comparison of HRUs to planted switchgrass field boundaries in Monroe County, Tennessee

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Input data
- Existing land cover
- Soil type
- Elevation/slope
- Hydrology
- Prevailing climate
- Parameters for modeling perennial switchgrass growth
- Management (e.g., fertilizer use)

Soil and Water Assessment Tool (SWAT)

Conduct 3 sets of parallel runs on 63 subbasin pairs in order to test effects of converting individual hydrologic response units (HRUs) to switchgrass
- Baseline runs
- Individual HRU conversion runs
- All switchgrass runs

Projected changes in pollutant concentrations at each subbasin outlet based on land-use configuration selected
- Total suspended sediments
- Total nitrogen
- Total phosphorous

Supplemental input data
- Empirical US grid of switchgrass yields
- University of Tennessee Institute of Agriculture economic information

Policy Analysis System (POLYSYS)

Values by crop type
- Price
- Yield

Biomass Location for Optimal Sustainability Model (BLOSM)

Objective functions can consider
- Farm profit
- Water quality impacts at sub-basin level
  - Total nitrogen concentration
  - Total phosphorus concentration
  - Total suspended sediment concentration

Assumptions
- Meet switchgrass production target
- Convert only agricultural or pasture/hayland
- Possibly constrain total quantity of agricultural land converted

Optimal spatial locations for planting bioenergy crops to meet specific objectives

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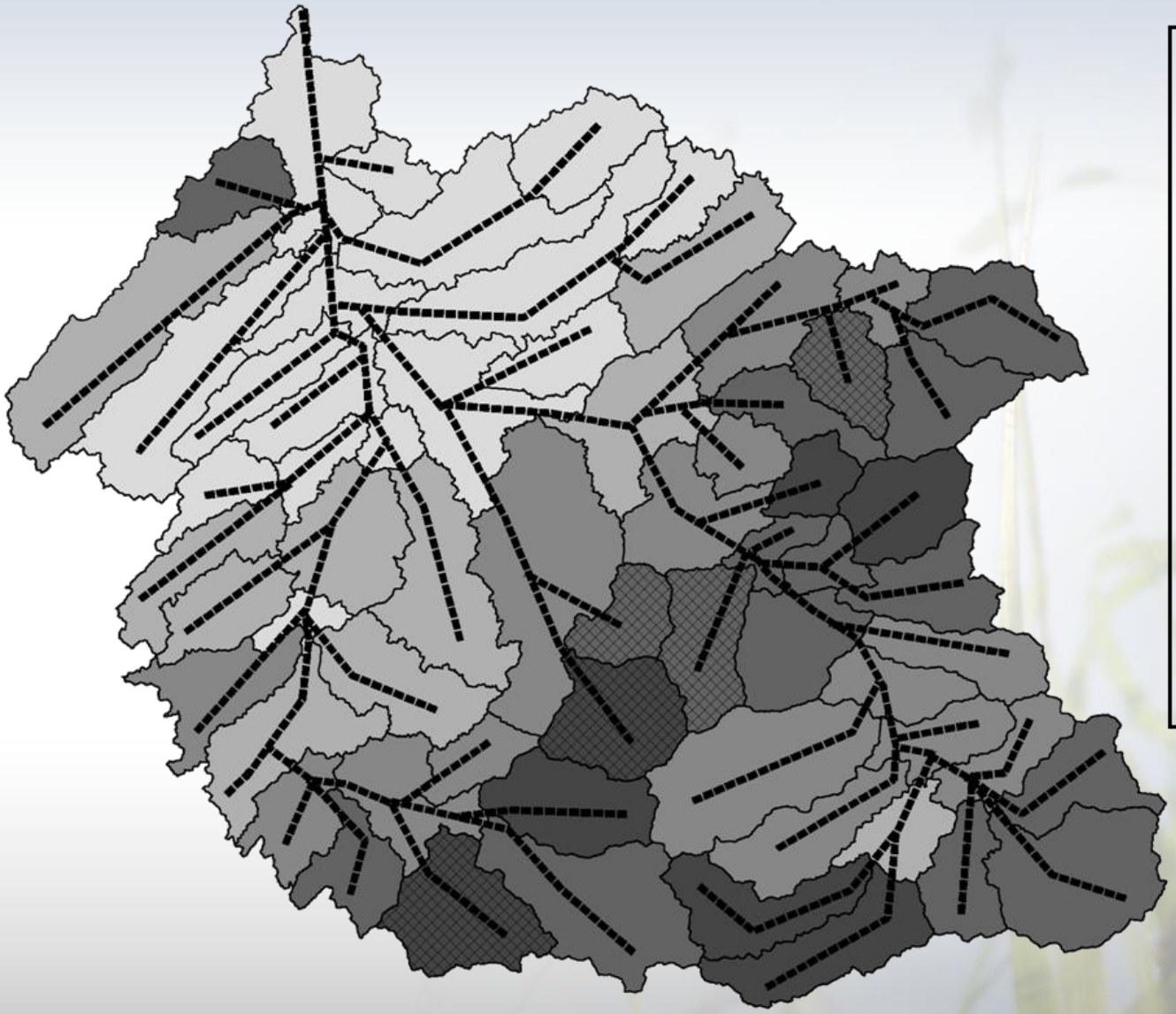
Economic & yield information for BLOSM were obtained from data collected for the Billion Ton Study (BTS) Update

- Comparison of local net revenues:

Commodity	Average Yield	Cost	Return	Net Revenue
Corn	75.3 quintals/ha (120 bushels/acre)	$986/ha ($399/acre)	$1112/ha ($450/acre)	$126/ha ($51/acre)
Switchgrass	13,450 kg/ha (6.0 tons/acre)	$956/ha ($387/acre)	$1080/ha ($437/acre)	$124/ha ($50/acre)
Pasture/hayland	5604 kg/ha (2.5 tons/acre)	$744/ha ($301/acre)	$1038/ha ($420/acre)	$294/ha ($119/acre)

- County-level crop yields for existing corn and pasture/hayland
- Projected switchgrass yields derived from an empirical US grid of lowland switchgrass by Jager et al. (2010)

Projected switchgrass yields for the LLT Watershed



Legend

- Subbasins
- No land available for switchgrass
- Simplified stream network

Potential Switchgrass Yield
metric tonnes/ha/yr
(dry tons/acre/yr)

- 16.2 - 16.6 (7.24 - 7.43)
- 16.7 - 17.6 (7.44 - 7.89)
- 17.7 - 18.8 (7.90 - 8.40)
- 18.9 - 19.9 (8.41 - 8.88)
- 20.0 - 21.8 (8.89 - 9.74)

Derived from map by Jager HI, Baskaran LM, Brandt CC, Davis EB, Gunderson C, and Wullschleger SD (2010) Empirical geographic modeling of switchgrass yields in the United States. **Global Change Biology Bioenergy** 2:248–257.

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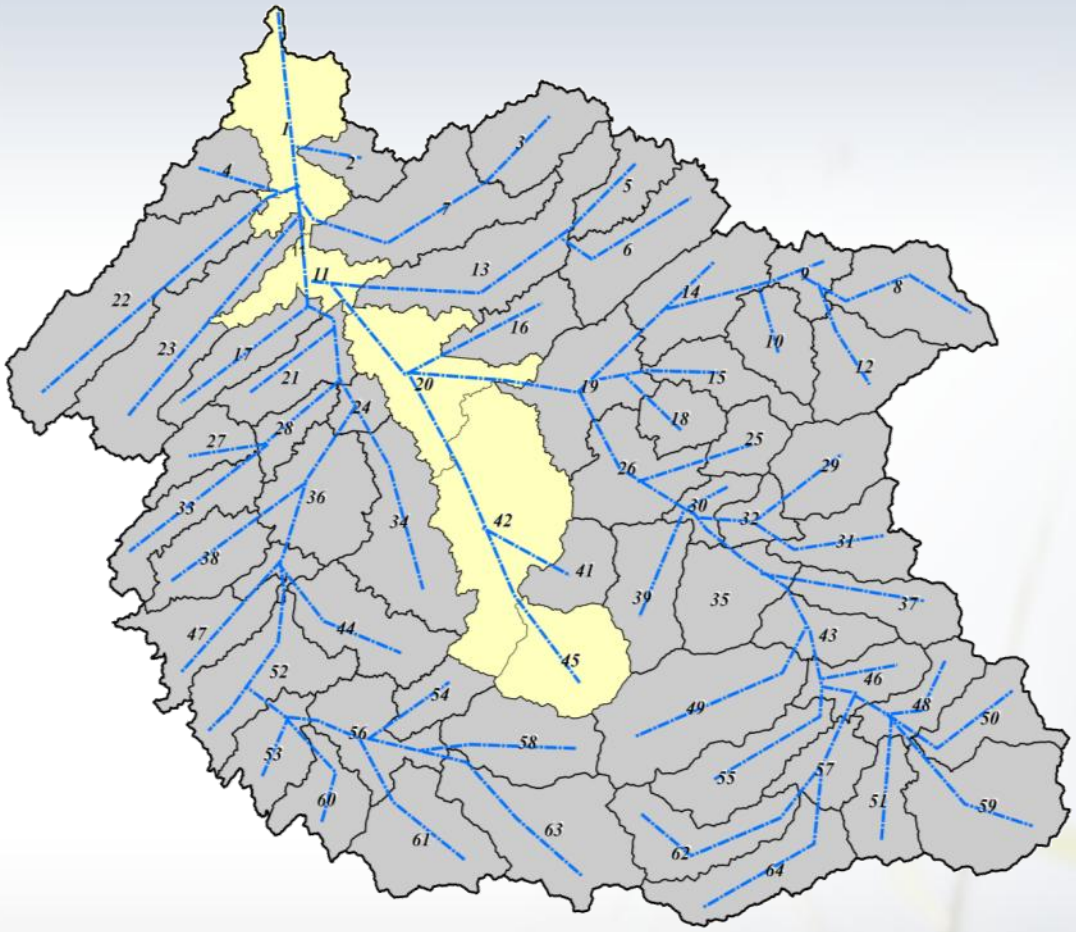
Subbasins and stream flow network used to track flow of pollutants during optimization:



Primary objective function used for optimization:

$$\text{maximize } p\sum_{i=1}^{H} r_i x_i + \sum_{Q=N,P,S} \frac{w_Q}{B} \sum_{i=1}^{H}\sum_{k=1}^{B} a_{Qik} x_i$$

Variables used :

Symbol	Description	Units
Q	Water-quality metric; either N (total nitrogen concentration), P (total phosphorus concentration) or S (total suspended sediment concentration)	mg/L
k	Subbasin ID; numbered from 1 to 64, with 1 being the mouth of the entire Lower Little Tennessee watershed	None
b_{Qk}	Baseline value for water-quality metric Q in subbasin k	mg/L
i	Hydrologic response unit (HRU) ID; unique combinations of slope, soil type and current land cover generated by the Soil Water Assessment Tool (SWAT) hydrologic model; numbered from 1 to 6965	None
a_{Qik}	Effect on water-quality metric Q in subbasin k from conversion of HRU i to switchgrass	mg/L
r_i	Expected change in net revenue from converting HRU i to switchgrass; based on outputs from the Policy Analysis System (POLYSYS) economic model	$
x_i	Proportion of HRU i converted to switchgrass; ranges from 0 (no conversion) to 1 (100% of area converted)	None
p	Weight assigned to profit in objective function (assumed to be nonnegative)	None
w_Q	Weight assigned to water-quality metric Q (assumed to be negative)	None
H	Number of HRUs	None
B	Number of subbasins	None
T*	Target tonnage of switchgrass	Tons
t_i	Tons of switchgrass contributed by conversion of HRU i	Tons

BLOSM was used to explore 6 possible production scenarios designed to maximize different sustainability objectives

Scenario	Sustainability Objective(s)
1. Minimize Nitrogen	Minimize concentrations of total nitrogen (i.e., the sum of organic nitrogen, nitrate, nitrite, and ammonium) at the outlet of the LLT watershed
2. Minimize Phosphorus	Minimize concentrations of total phosphorus (i.e., the sum of organic and inorganic phosphorus) at the outlet of the LLT watershed
3. Minimize Sediment	Minimize concentrations of total suspended sediments at the outlet of the LLT watershed
4. Maximize Profit	Maximize total economic profit from land conversion to switchgrass throughout the LLT watershed
5. Balanced Objectives	Achieve all three water-quality objectives (Scenarios 1-3) to the extent possible while also maximizing economic profit (Scenario 4) to the extent possible, thus achieving a "Balanced" solution
6. Limit Agricultural Land Conversion	Run the "Balanced" solution (Scenario 5) with the additional constraint that no more than 25% of the land-area conversion can occur at the expense of cropland **(per BTS Update)**

Results for the Lower Little Tennessee Watershed

(assuming production of 65,000 tons of switchgrass)

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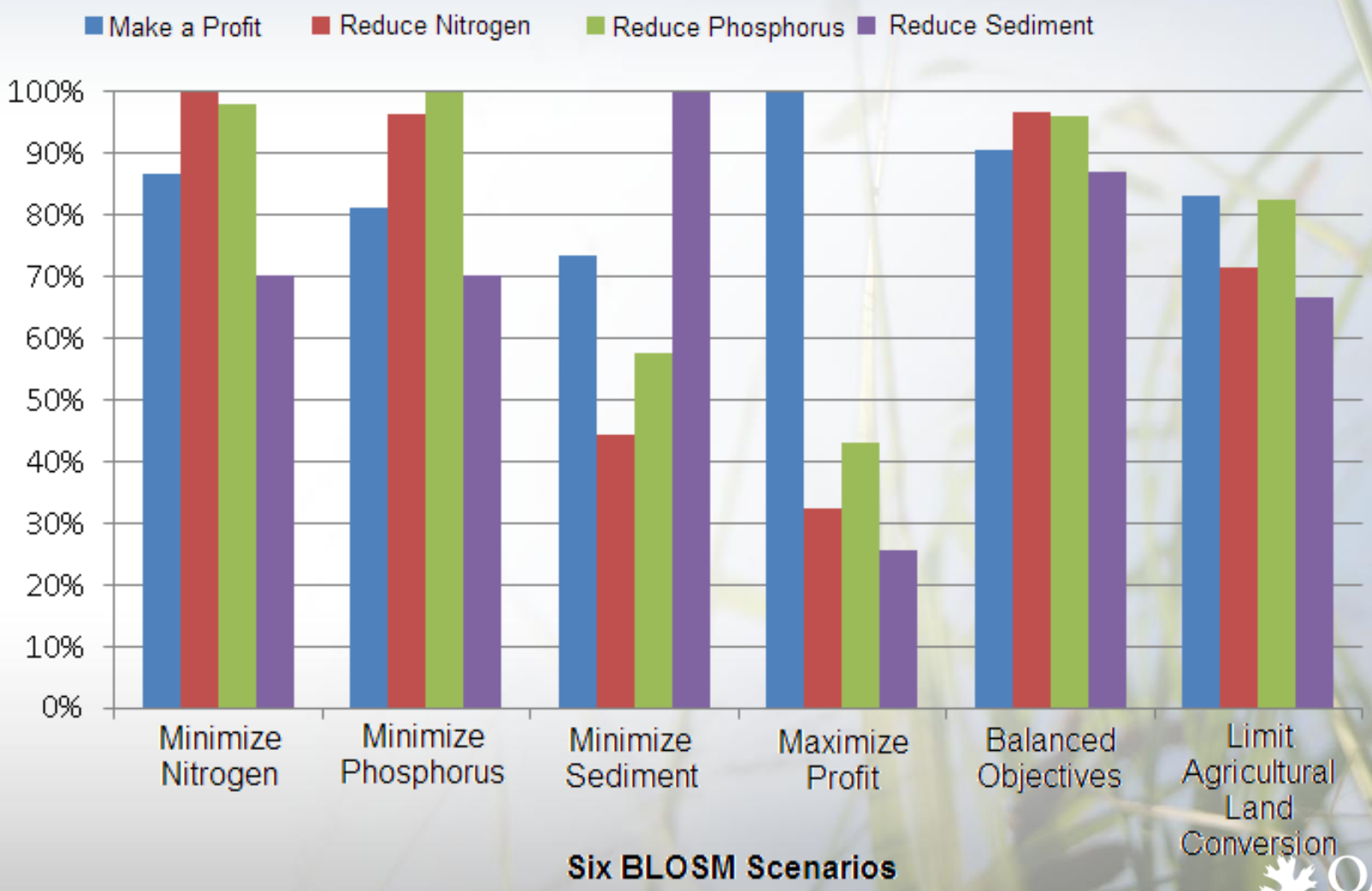
BLOSM projections of % maximum achievable for 4 sustainability criteria under 6 scenarios



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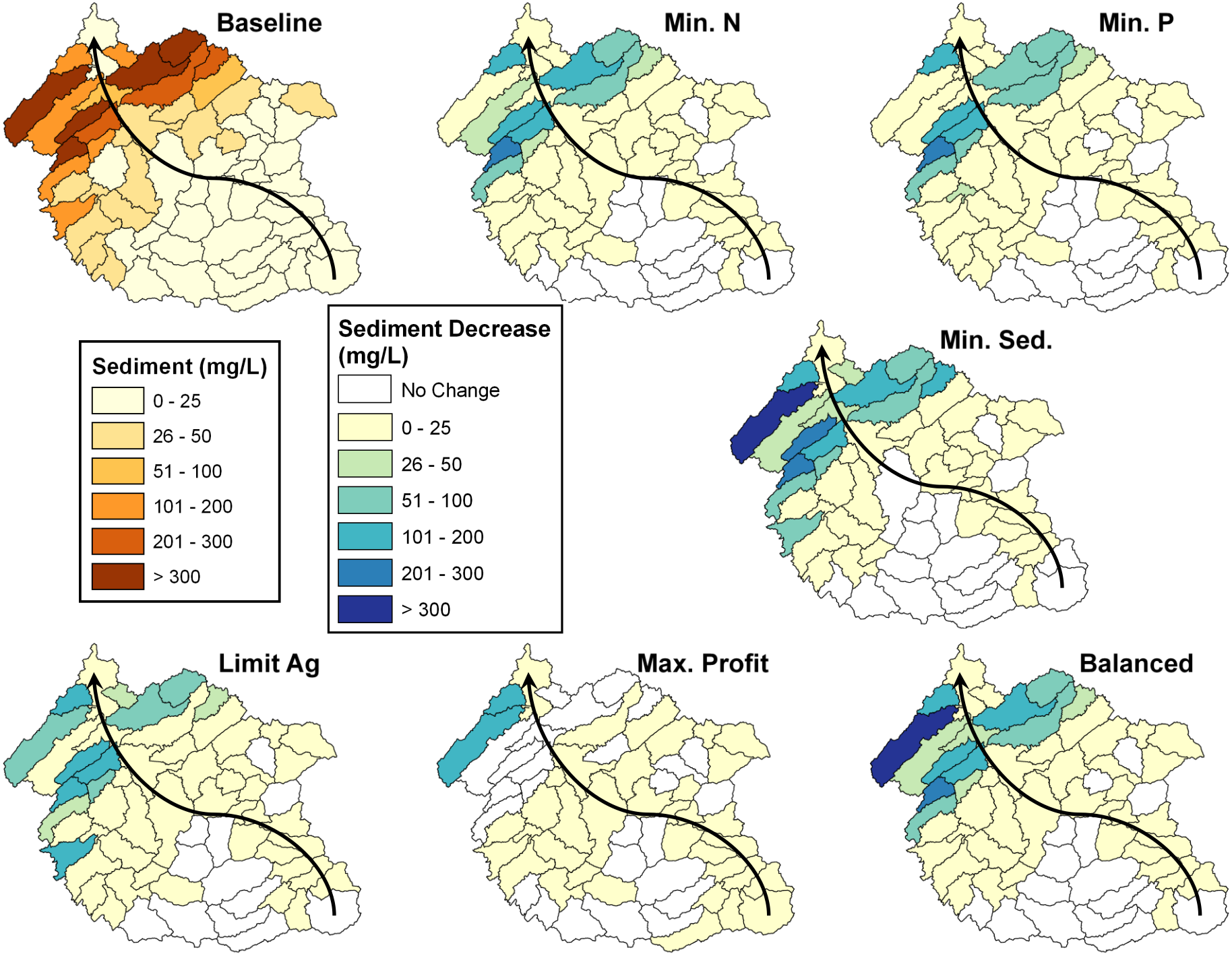
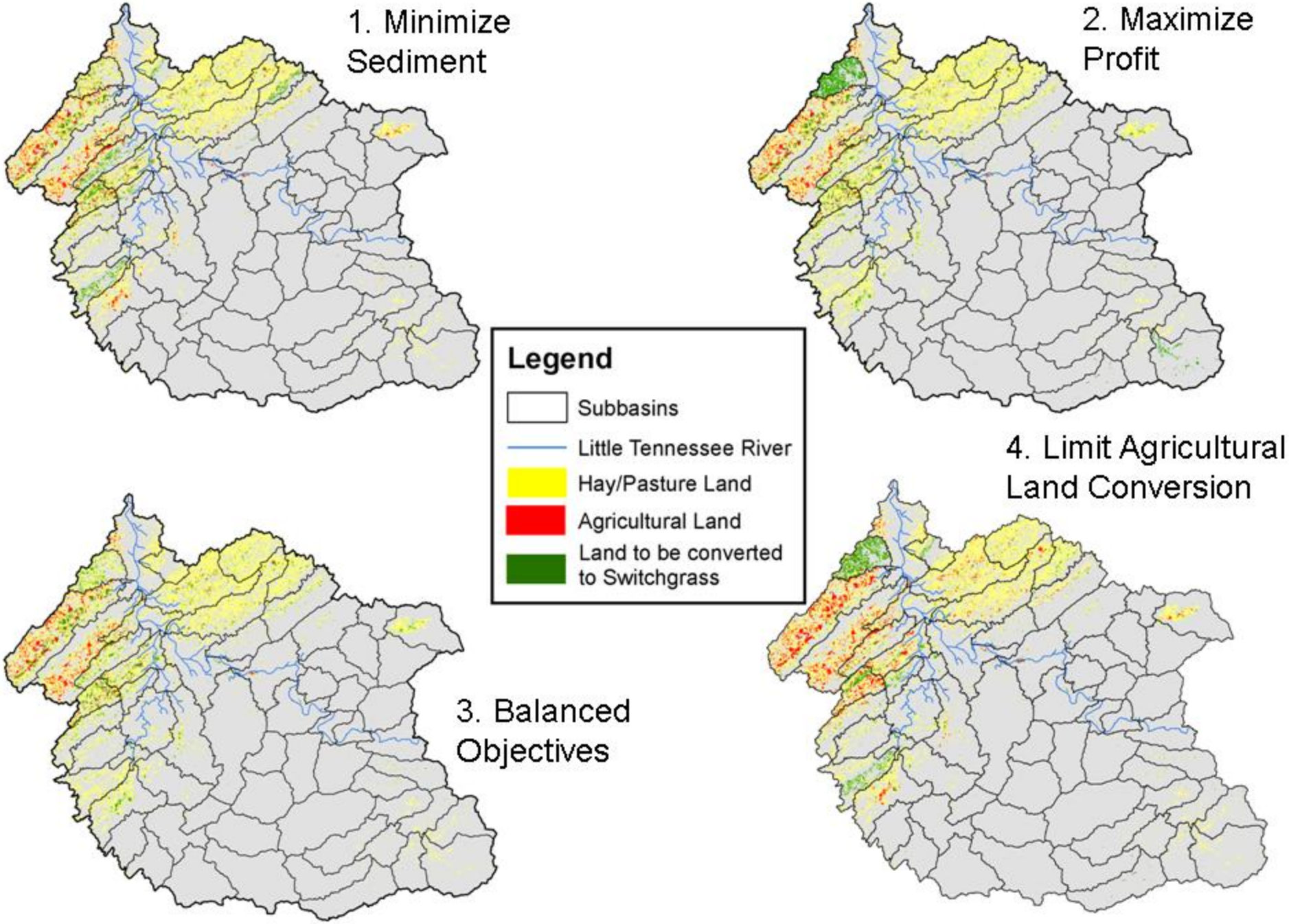

Baseline
Min. N
Min. P
Min. Sed.
Limit Ag
Max. Profit
Balanced
Sediment (mg/L)
0 - 25
26 - 50
51 - 100
101 - 200
201 - 300
> 300
Sediment Decrease (mg/L)
No Change
0 - 25
26 - 50
51 - 100
101 - 200
201 - 300
> 300


1. Minimize Sediment
2. Maximize Profit
3. Balanced Objectives
4. Limit Agricultural Land Conversion
Legend
Subbasins
Little Tennessee River
Hay/Pasture Land
Agricultural Land
Land to be converted to Switchgrass

Next Steps

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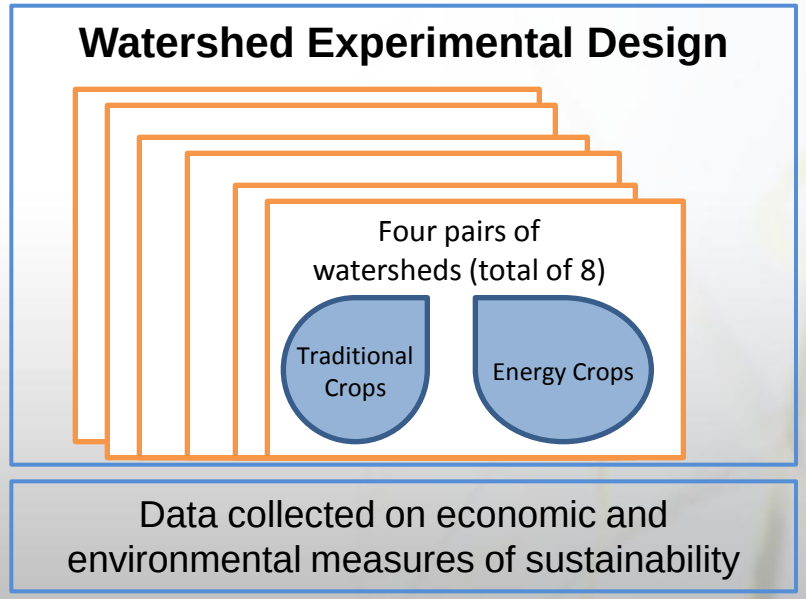
Experimental testing using paired watersheds near Vonore

Hypothesis: Bioenergy systems can be designed to be sustainable at a watershed scale

Methodology: Test using economic and environmental indicators measured from paired watersheds

- Pairs are similar except for bioenergy crops
- Use data on environmental effects associated with feedstocks already being produced to supply the Vonore Demonstration-scale (250 Mgal/yr) Biorefinery in East Tennessee
- Validate BLOSM results for the Lower Little Tennessee watershed

Funding: Hydrologic sampling of 4 watershed pairs to be funded by the US Department of Agriculture's support to the Southeastern US Regional Partnership known as IBSS (Integrated Bioenergy Supply System).



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Conclusions

- Case study results indicate that a combined economic and environmental optimization approach can achieve multiple sustainability objectives simultaneously
- BLOSM approach in conjunction with BTS data can be applied to other:
  - feedstocks
  - sustainability objectives
  - regions
- Real-world data will be critical to ensuring success of modeled landscape designs

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For more information, you may:

- Visit our Center for BioEnergy Sustainability (CBES) website at www.ornl.gov/sci/ees/cbes/
- Visit our BLOSM interactive results website at http://blosm.ornl.gov
- Contact me at parishes@ornl.gov

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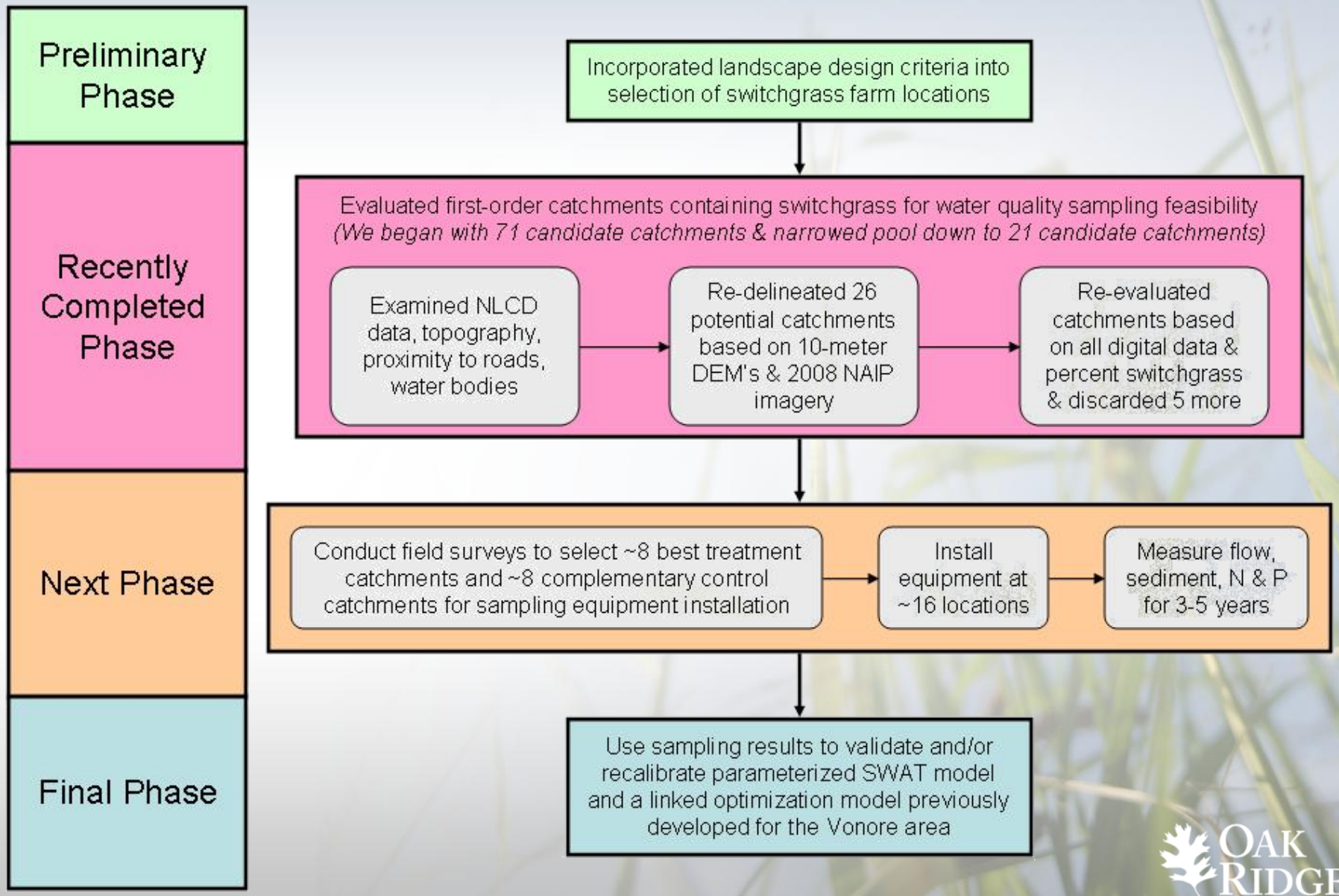
Selection of catchments for flume installation



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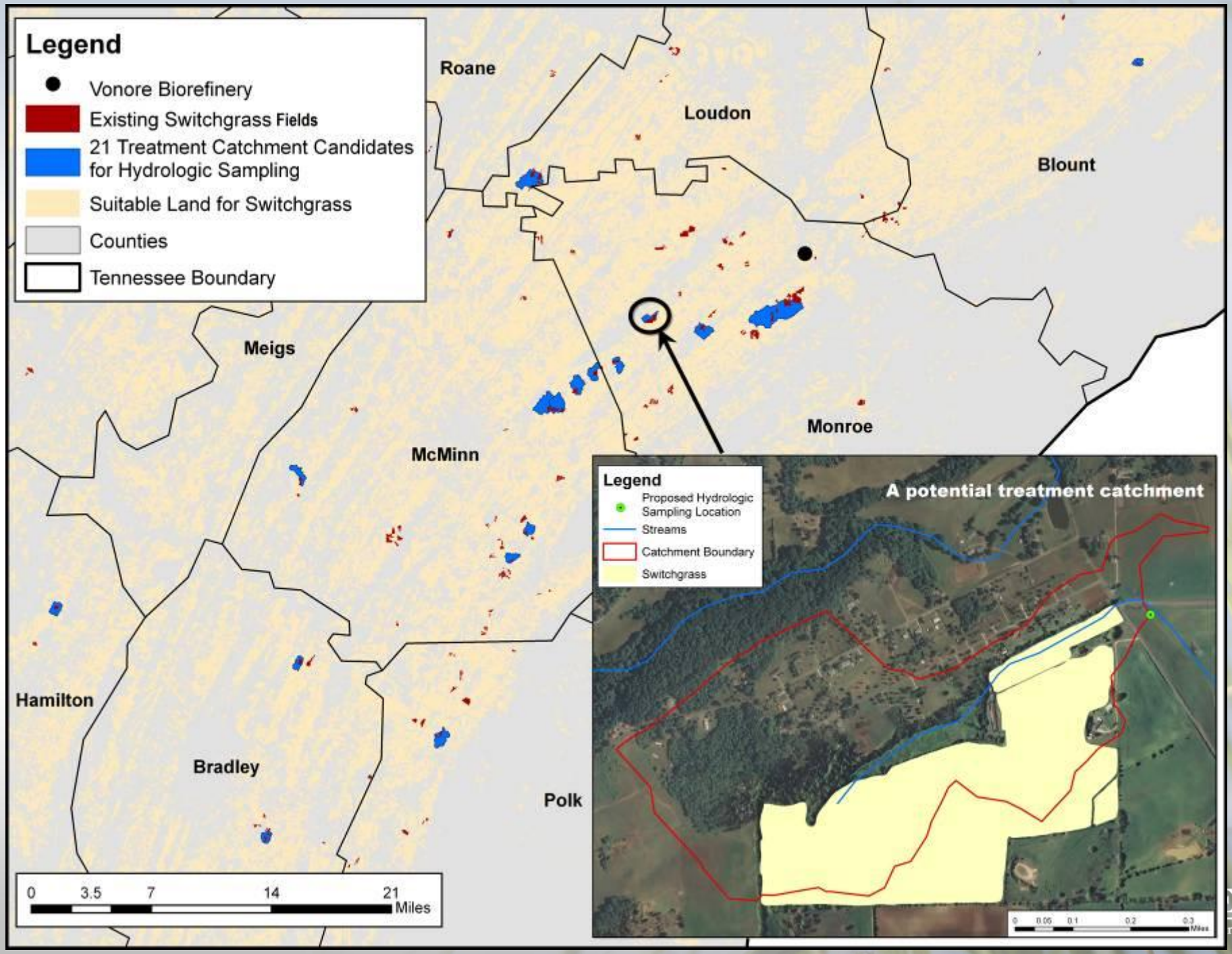
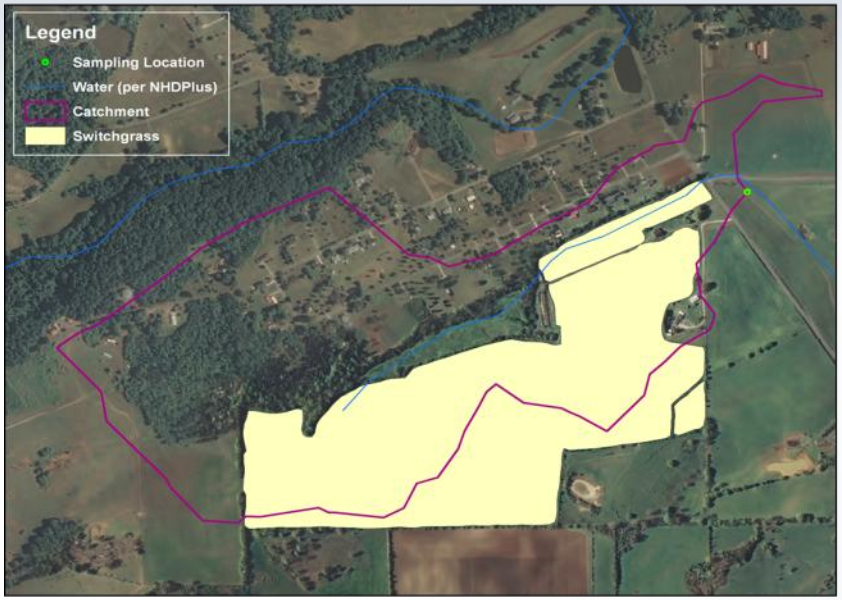

Legend
Vonore Biorefinery
Existing Switchgrass Fields
21 Treatment Catchment Candidates for Hydrologic Sampling
Suitable Land for Switchgrass
Counties
Tennessee Boundary
Roane
Loudon
Blount
Meigs
Monroe
McMinn
Hamilton
Bradley
Polk
0 3.5 7 14 21 Miles
Legend
Proposed Hydrologic Sampling Location
Streams
Catchment Boundary
Switchgrass
A potential treatment catchment

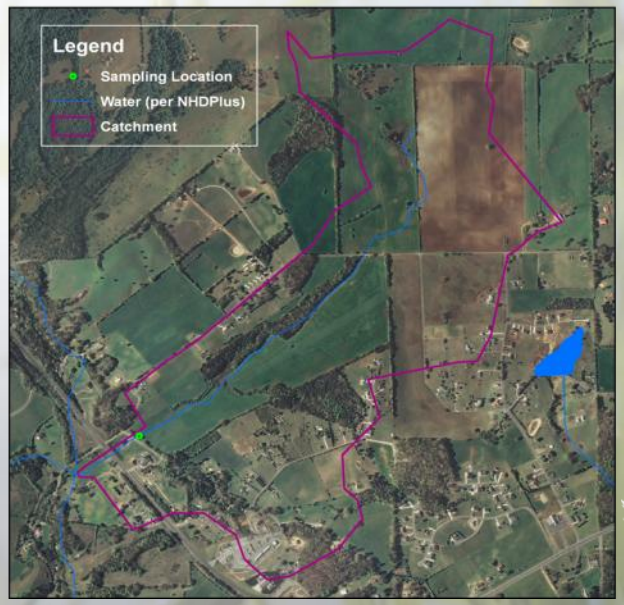
Treatment catchments to be paired with control catchments



Left: 1st order treatment catchment #24 containing 36% switchgrass; total area of 76 hectares

Below left: Catchment #24 prior to treatment

Below right: Control catchment selected for its similar characteristics



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