Simulating water quality and hydrology responses to growing biomass feedstocks in the Mississippi River Basin

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Because of concerns about Gulf hypoxia, a number of government agencies and other entities are working to reduce nutrient loadings to Mississippi River Basin (MRB).

- USDA ARS developed assessments on contributions of MRB tributary basins and potential reductions in nutrient and sediment loadings that can be achieved through conservation practices.
- Federal agencies in the Hypoxia Task Force led by the USEPA are working with the twelve MRB states to identify priority watersheds and develop state nutrient reduction strategies.
- NGOs, stakeholders, and local communities forged partnerships to implement a plan for reducing nutrient losses.
Concerns about corn ethanol and its impacts motivated this DOE funded research.

These two projects evaluated the potential effects of adding future cellulosic biomass production in the Mississippi River Basin.

Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River

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Corn cultivation in the United States is expected to increase to meet demand for ethanol. Nitrogen leaching from fertilized corn fields to the Mississippi-Antilalafaya River system is a primary cause of the bottom-water hypoxia that develops on the continental shelf of the northern Gulf of Mexico each summer. In this study, we evaluate additional land use scenarios with projected increased corn and water cycling and downstream transport of nitrogen and water across the Mississippi-Antilalafaya River Basin to agricultural land use practices and climate variability (4, 10–16). First, we used USDA data to generate a series of spatially explicit land use scenarios including a control case (based on 2004–2006 mean land use) and other cases with increased corn cultivation in the central, southern, or northern Mississippi River Basin. Second, we used the SWAT model to simulate the potential impacts of these additional land use scenarios on water quality in the Gulf of Mexico. The results indicate that increased corn cultivation has a significant and substantial effect on water quality in the Gulf of Mexico.
Scientific questions

What are the contributions of tributaries on downstream water quality in the Gulf?

Can loadings be minimized by conservation practices in conjunction with biomass production?

How might nutrient loadings to the Gulf change under assumptions about future biomass production?

How can we meet food and bioenergy needs while maintaining or decreasing nitrogen, phosphorus, and suspended sediments run-off in the Mississippi River Basin?

Where are there trade-offs or complementarities between biomass production and water quality?
Watershed modeling of the Mississippi River Basin

- Joint effort by Argonne National Laboratory (ANL) and Oak Ridge National Laboratory (ORNL) with support of DOE Bioenergy Technologies Office
- Developed watershed models for each river basin in the Mississippi River drainage to assess water quality outcomes for biomass production
  - Historical baseline landscape
  - Potential biomass future scenarios
- Evaluated management practices associated with growing biomass crops
  - Multi-purpose buffers
  - Tillage
  - Cover crops
  - Restricting tile drainage
  - Nitrogen fertilizer management
Future biomass production scenarios

- DOE’s resource assessments were conducted in 2011 and 2016
- A partial equilibrium model for the US agricultural sector estimated the most profitable allocation of land to crop options, including biomass crops and residues, from the producer’s perspective.

Agricultural sector in all 3,110 counties
- Available ag and pasture land is based on the USDA baseline for 10 y and then interpolated linearly.
- Each year, price depends on demand and previous-years supply for food, feed, industry, and export.
- Profitability is estimated from crop budgets and yields, for a range of fixed farmgate prices for biomass.
- Biomass yields are modeled for food, feed, fiber and energy crops.
- Represents 8 major crops and hay, livestock, food and feed markets.

For more information, see the Billion Ton 2016 Report: www.energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf
Economic projection of future landscapes ($60/dt, 1%)

https://bioenergykdf.net/map?model=bt16

Corn stover

Miscanthus

Coppice wood (willow)

Switchgrass
Composite transitions in land-area 2015 to 2040

**Base-case scenario**
- 1% annual yield increases
- $60/dt farmgate price

**High-yield scenario**
- 3% annual yield increases
- $60/dt farmgate price
Watershed modeling of the Mississippi River Basin

- The Soil Water Assessment Model (SWAT) was used to evaluate current and potential future landscapes.
- MRB tributary basin models
  - Upper Mississippi River Basin (ANL)
  - Ohio / Tennessee River Basin (ANL/ORNL)
  - Missouri River Basin (ANL)
  - Arkansas White-Red River Basin (ORNL)
  - Lower Mississippi River Basin (ANL)
How can we meet sustainability requirements for integrated production of food, feed and fuel?

Where might there be hotspots with potential impairments to water quality and what are opportunities for improvement?

- Biofuel feedstock: grain, residue, perennial, energy crop
- Land use changes
- Agricultural management and practices
- Yield increase
- Future production scenario
- Climate
- Basin and watershed scales
SWAT models represent historical landscapes

Topography

Water use

Sub basin

Land use, crop rotation

Fertilizer

Soil type

Calibration and validation with 20-years measurements

Other model drivers, inputs

- Climate
- Tile drainage
- Tillage
- Irrigation
- Point source
- Reservoirs

Integrated Simulation

Hydrologic Cycle

Crop Growth

Nutrient Cycle

Routing

Hydrology:
- Runoff
- Evapotranspiration
- Groundwater
- Soil moisture

Water Quality:
- Nutrients
- Erosion
- Pesticides

Crops:
- Biomass
- Yield
Future scenario

- Soy bean acreages increase by 130 ha.
- Wheat acreages increase by 23 ha.
- Corn acreages remain same.
- Switchgrass grown primarily in pasture land in Kansas River watershed.

Baseline year: 2007
Identify hot spots for nitrogen, phosphorus & sediment loadings in Missouri River Basin under a future scenario

Upper Mississippi River Basin (UMRB)
Incorporate land use and management in the Upper Mississippi River basin

Scenario

- Corn increases 3.8 million acres.
- Corn yield increase.
- 1.5 million acre increase in idle land.
- Corn stover is harvested to a total of 48 dry metric tons.
- 4.8 million decrease in pasture and hay.
- No till increases 3.9 million acres; conventional- and reduced-tillage decrease 1.3 million acres.

Changes in corn yield, fertilizer application, and tillage, and harvest indices

Compare with baseline year 2006

Demissie, Yan, Wu, 2012. ES&T
Estimated changes of nutrients, sediments, and hydrology under a potential scenario

Changes relative to baseline year (2006)

<table>
<thead>
<tr>
<th>Nitrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Phosphorus</td>
</tr>
</tbody>
</table>

Effects associated with biomass production are mixed

- Nitrogen, Phosphorus
- Sediment
- Flow
- Evapotranspiration
- Soil moisture content

Demissie, Yan, Wu, 2012. ES&T
How do switchgrass, stover harvest, and yield influence water quality and quantity in Upper MRB?

- On per volume of fuel production basis, nutrient and sediment loadings decrease when crop yield and cellulosic biomass production from stover and switchgrass increases.
- Evapotranspiration increases whereas surface runoff and flow decreases.

Biofuel production (Billion gallons)

<table>
<thead>
<tr>
<th>Year</th>
<th>Switchgrass</th>
<th>Corn yield increase</th>
<th>Stover 24% harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>5.3</td>
<td>6.0</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Baseline year: 2006

Potential effects of potential biomass production on water quality quantity in Ohio River Basin

Scenarios

• 1% yield increase, $50/dry ton biomass.
  – Corn, soybean, wheat, and idle land areas to gain 444, 91, 26, and 451 thousand hectares; hay and pasture to decrease 1012 thousand hectares.
  – Stover harvest up to 18%, total 7.3 million dry-tons.
  – Increased conservation tillage and decreased conventional tillage.
• Business as usual (BAU): 1% corn yield increase.
• Compare with baseline year 2006.

Tennessee River Basin (TRB)
SWAT simulation of biomass crops in the Tennessee River Basin

- We compared two potential future scenarios, a base case and high-yield scenario with the current landscape.
- Dominant biomass crops included willow, miscanthus, and switchgrass.
- SWAT model calibration and comparisons against data were challenging because of the influence of dams and the sparse availability of field measurements for this river basin.
- We developed solutions including comparison against synthetic, intermediate response variables derived from gage-derived measurements. This required the development of a new calibration methodology, SWATopt.
- SWAT model performance was reasonably good (median model efficiencies = 0.83 and 0.72 for runoff calibration and validation; percent biases generally within ±25% for runoff and ±70% for water quality) for most subbasins.
Future biomass crops in the Tennessee River Basin

Hay was converted to miscanthus and willow, whereas pasture converted to switchgrass (overall pasture increased).
Simulated water quality in the Tennessee River Basin

Key findings:
- Large decreases in median total N loadings and concentrations...
- ... because less fertilizer was required to grow miscanthus and willow than hay.
- No significant change in sediment or total P (opposite sig. responses of soluble and sediment-bound components).

Definitions
- TN: total N
- ORGN: organic N
- NO3: nitrate
- SURNO3: nitrate in surface runoff
- LATNO3: nitrate in lateral flow
- GWNO3: nitrate in groundwater flow
- TSS: total suspended sediment
- TP: total P
- ORGP: organic P
- SOLP: soluble P
- SEDP: mineral P attached to sediment

MINP = SOLP + SEDP
SWAT-simulated changes in water quality from a 2015 baseline in the Tennessee River Basin

**Nitrate**

**Total phosphorus**

**Total suspended sediment**
Arkansas White-Red River Basin (AWRRB)
Current landscape

Future scenario

$50 farmgate price for switchgrass
1% annual yield increase
Results for Arkansas-White-Red River basins

Key findings:
- Substantial decrease in simulated median nitrate loadings and TN loadings
- Smaller decrease in median total phosphorus (TP) and sediment (TSS)
- Smaller decrease in water yield
SWAT-simulated changes in water quality for the Arkansas-White-Red River basin
Four major basins contribute to Lower Mississippi River basin

Spatial distribution of nutrients and sediments from MRB to the Gulf of Mexico

- Upper Mississippi River basin accounts for ~50% of nitrogen loadings to Lower Mississippi river basin.
- Ohio/Tennessee river basin contributes to a majority of flow and phosphorus.
- Missouri River basin is responsible to most of the sediments.
- Lower Mississippi River basin contributes 17% of the streamflow, 42% of the sediments, 10% of the nitrate, and 16% of the phosphorus into Gulf of Mexico.

Cross-cutting insights

- The Upper Mississippi, Ohio River, and Missouri River basins have been identified as major sources of nitrogen, phosphorus, and suspended sediments to the Gulf of Mexico.

- Our results suggest that loadings in these and other basins can be reduced by growing biomass such as switchgrass, short rotation woody crops and the degree of reductions can vary across tributary basins.

- Assumptions regarding biomass crop replacement and associated management (fertilizer, tillage, and others) were important to the outcomes.

- In watersheds and economic scenarios where annual crops, hay, or pasture were replaced by perennial biomass crops, SWAT predicted improvements in water quality. Harvesting annual crop residues also had beneficial effects on reducing nitrogen.

- Evapotranspiration increased, surface runoff and soil water decreased under the potential scenarios examined in most basins.

- In all basins, geographic variation in water quality outcomes occurred, with some areas serving as nutrient or sediment sources and others as sinks relative to that simulated from a current landscape.
Lessons learned

- As DOE labs, our expertise is in modeling management of biomass crops, economic assumptions, projected land management, and simulating water quality implications.

- Model fitting at large regional scales was challenging, and approaches such as functional validation and use of synthetic data such as USGS regional loading models were helpful.

- Watershed modeling requires attention to many variables not of immediate interest (conventional crops, tile drainage, point sources, dams and reservoirs). Therefore collaborations, e.g., SWAT developers, USGS, USACE, TVA were important.
Conservation practices

- Biomass feedstock specific
- For short-rotation woody crops, filter strips
- For perennial grasses, fertilization
- For conventional crops:
  - Stover removal rates
  - Fertilizer management (type, timing)
  - Riparian buffers
  - Tile drain mitigation

Two river basins with different feedstock profiles

Arkansas-White-Red River Basin

Iowa River Basin

2012

2040 Base case

2040

Pasture/Hay
Forest
Shrubland/Fallow
Corn/Soy/Sorghum/Wheat
Switchgrass
Urban

Pasture/Hay
Mishcanthus
Urban

2012

2040

Arkansas-White-Red River Basin

Iowa River Basin

Pasture/Hay
CORN/SOY/SORGHUM/WHEAT
Mishcanthus
Urban

Pasture
Forest
Wetland

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
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Argonne National Laboratory
‘Best’ practices revealed trade-offs between indicators

- Tile drains on lands steeper than 1% slope rarely benefited residue yield or water quality.
- No-till favored higher yields, and reduced sediment and TP (but not nitrate) loadings.
- Filter strips improved water quality for willow and poplar, with some cost to yield. Harvest of strips can be considered in future.
- Residue removal from annual crops increased sediment but decreased nutrient loadings. This assumed fixed fertilizer input.

Larger trade-offs between yield and nitrate than yield and TSS or TP, primarily caused by variation in fertilizer amounts.
Trade-offs: Locally ‘best’ practice depends on indicator

NO3: Conventional till, least fertilizer, tiles only on flat land

TP: Mostly no till, least fertilizer, tiles only on flat land

Yield: Mostly no till, high fertilizer, tiles only on flat land

Fertilizer
101 kg N/ha (pink)
135 kg N/ha (blue)
168 kg N/ha (green)
201 kg N/ha (yellow)
235 kg N/ha (red)

Tillage
NT = no till
CT = conventional till

Tile drains
0% to 1% slope
0% to 2% slope

Win-win opportunities occur where the same practice benefits yield and water quality indicators
### Geospatial results – Iowa River Basin

<table>
<thead>
<tr>
<th></th>
<th>Tile drain (&lt;2%)</th>
<th>Cover crop</th>
<th>Nitrogen management</th>
<th>Buffer 50m, basin</th>
<th>Buffer 50m, main stem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total nitrogen (Kg)</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
</tr>
<tr>
<td>Nitrate (Kg)</td>
<td><img src="image6" alt="Image" /></td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
</tr>
<tr>
<td>Total phosphorus (Kg)</td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
<td><img src="image15" alt="Image" /></td>
</tr>
<tr>
<td>Sediment (metric ton)</td>
<td><img src="image16" alt="Image" /></td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
<td><img src="image19" alt="Image" /></td>
<td><img src="image20" alt="Image" /></td>
</tr>
</tbody>
</table>

- Loadings of nutrients and sediments exhibit strong heterogeneity across the landscape.
- Removal of sediments and phosphorus is correlated with the size of flow and stream network when buffer is installed.
**Key findings – Iowa River Basin**

<table>
<thead>
<tr>
<th>Conservation Practice Scenarios</th>
<th>Suspended Sediments</th>
<th>Total Phosphorus</th>
<th>Total Nitrogen</th>
<th>Nitrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffer 30m, main stem of Iowa River</td>
<td>70.5%</td>
<td>7.9%</td>
<td>8.2%</td>
<td>6.2%</td>
</tr>
<tr>
<td>Buffer 50m, main stem of Iowa River</td>
<td>70.8%</td>
<td>8.6%</td>
<td>8.9%</td>
<td>6.9%</td>
</tr>
<tr>
<td>Buffer, 50m, entire Iowa River stream network</td>
<td>80.3%</td>
<td>22.7%</td>
<td>22.7%</td>
<td>10.8%</td>
</tr>
<tr>
<td>Cover crop</td>
<td>37.0%</td>
<td>27.4%</td>
<td>18.5%</td>
<td>19.0%</td>
</tr>
<tr>
<td>Nitrogen fertilizer management (scheduling)</td>
<td>5.6%</td>
<td>9.9%</td>
<td>10.9%</td>
<td>11.4%</td>
</tr>
<tr>
<td>Tile drain (&lt;2% slope)</td>
<td>1.8%</td>
<td>1.7%</td>
<td>27.5%</td>
<td>28.6%</td>
</tr>
</tbody>
</table>

- Riparian buffer is most effective in reducing suspended sediments. Degree of reduction increases with buffer coverage.
- Limiting tile drainage to the land with less than 2% slope could significantly reduce nitrate loadings to downstream communities.
- A combination of the four conservation practices could result in substantial improvement in this region.
- Results may be applicable to regions with similar soil, climate, landscape, and crop systems.
Simulation of riparian buffers in Lower Mississippi River basin

Changes of nutrients and sediments in regional watersheds relative to baseline year 2012

Benefit analysis of riparian buffer in agriculture land in Lower Mississippi River Basin

- Buffer can be harvested as biomass.
- Use nutrients trapped in the soil to grow switchgrass as buffer.
- Factors considered: buffer installation, fertilizer savings, biomass value, crop production.

Findings:
- Net returns increase with increase of switchgrass yield, switchgrass market price, and fertilizer prices; and decrease with an increase of buffer installation cost and crop land loss to buffer.
- Results vary from state to state in the lower MRB.

Summary – Management practices and water quality

- Riparian buffers were highly effective at reducing loadings of sediment and phosphorus in lands growing annual crops and residues (IRB and LMRB).
- Filter strips for short-rotation woody crops and corn/soy bean were effective in reducing all loadings with no significant effect on willow yield (AWR and IRB).
- Cover crops were effective in reducing nutrients and sediments runoff from annual crop land with residual harvest (IRB).
- Avoiding tile-drains on >1% slope was effective in reducing nitrogen loadings and still provided a yield benefit (AWR and IRB).
- Scheduling of nitrogen fertilizer reduced nitrogen loadings comparable to that associated with planting a riparian buffer (IRB).
- Compared with conventional till, no-till production of annuals was associated with lower phosphorus and sediment loadings, but not lower nitrate loadings (AWR and UMRB).
- Integrating multi-purpose riparian buffer planted in switchgrass is an attractive strategy to effectively trap nutrient loss from agricultural land while producing biomass for energy production (LMRB).
- The profitability of implementing buffers is constrained by switchgrass price, the cost of installation of buffer, and loss of conventional crop acreage (LMRB).
References


References


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