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**Grey Water Footprint and Economic Tradeoff Analysis of Switchgrass Supply Chain: A Case Study of
West Tennessee**

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INTRODUCTION

In West Tennessee, 96 percent of all households rely on ground water. Shallow aquifers in West Tennessee are at risk of contamination from the 1.1 million ha in crop production in the area. Low nitrogen uptake efficiency with crop production leaves considerable nutrients to runoff into surface water, be retained in the soil, or leach into groundwater.

Growing switchgrass for biofuel production has the potential to use less water and fertilizer than traditional row crops. Displacing crop production with the large-scale production of switchgrass as a biofuel feedstock could reduce nitrate loadings to groundwater in west Tennessee; hence, lowering the risk of groundwater contamination. However, the high private costs of producing biofuel from switchgrass hinder its development for commercial use.

One way to account for the positive ecosystem services provided by switchgrass is through the concept of grey water footprint (GWF), or the volume of water needed to sufficiently dilute nitrate loadings to meet ambient water quality standards. Considering the positive externalities associated with reduced nitrate loadings can help the biofuel industry develop a more sustainable feedstock supply chain that balances both economic and environmental performance.

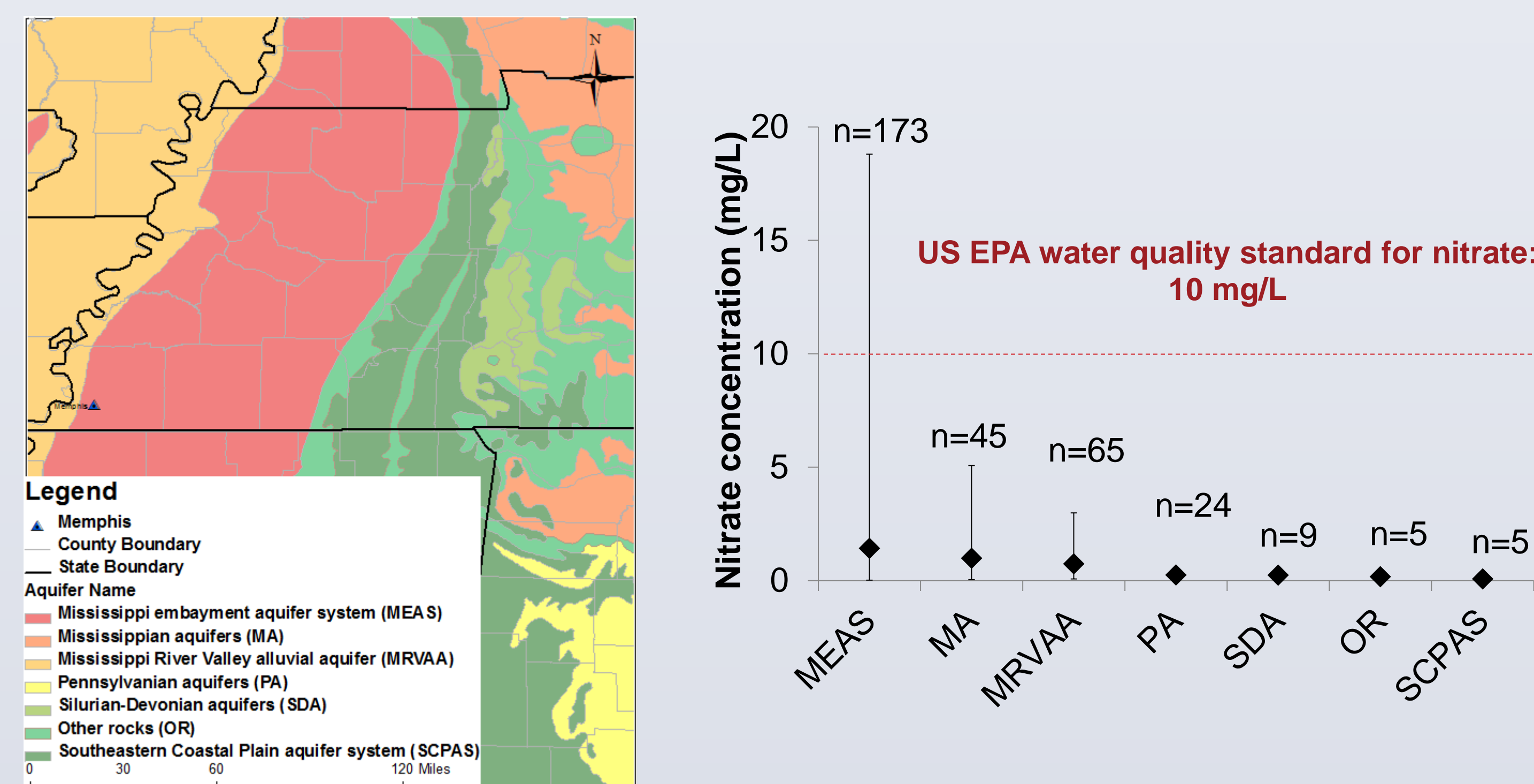


Figure 1. Observations of nitrate levels in west Tennessee aquifers (1980-2014)

OBJECTIVES

- Estimate GWF for different switchgrass supply chain configurations in West Tennessee; and
- Estimate the relationship between the costs of supplying switchgrass as a biofuel feedstock and GWF in West Tennessee.

DATA AND METHODS

- Cost data [opportunity cost ($C_{opportunity}$), feedstock production ($C_{production}$), harvest ($C_{harvest}$), storage ($C_{storage}$), transportation cost ($C_{transportation}$), capital cost of biorefinery ($C_{capital}$), and operational cost ($C_{operation}$)] were obtained from previous studies (Larson et al. 2010; Yu et al., 2014).
- GWF estimated using water footprint models (Aldaya et al. 2012), USGS groundwater quality data (USGS Water Resources, 2015) and Daycent water submodel nitrate loading for crop lands (p) and switchgrass (swg) ($Nload$) (Schimel et al. 2001).

ANALYTICAL MODEL AND ASSUMPTIONS

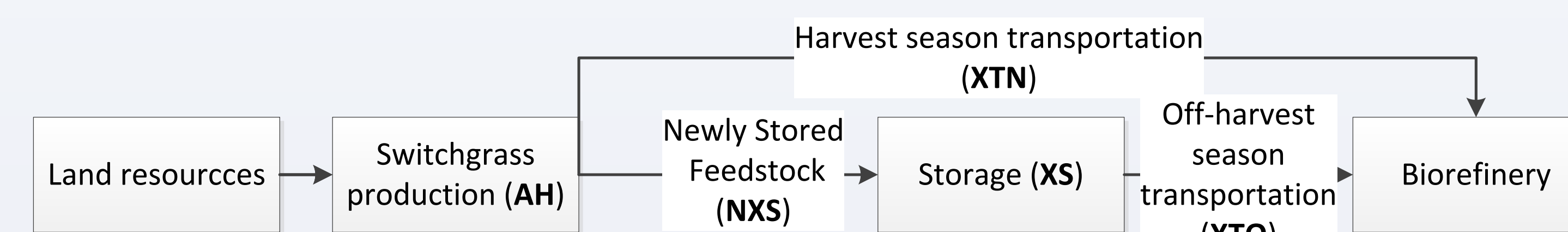


Figure 2. Flow diagram of the switchgrass supply chain

- Cost objective is to minimize total cost (TC) where:
$$TC = C_{opportunity} + C_{production} + C_{harvest} + C_{storage} + C_{transportation} + C_{capital} + C_{operation}$$
- Grey water footprint objective is to minimize GWF where:
$$GWF = \sum_i (Nload_{i,swg} \times \sum_p AH_{ip}) / (Permit - CN_i) - \sum_{ip} Nload_{i,p} \times AH_{ip} / (Permit - CN_i)$$
- The study area included all agricultural land in west Tennessee and a buffer area of 50 mile contiguous to the state border, and was downscaled to a 5 mile² resolution spatial unit (i).
- The background nitrate (N) level (CN) of groundwater was assigned from the estimated mean values from sample points in 2014 at spatial unit (i).
- Water quality standard for N was set as 10 mg/L (Permit).
- A multi-objective, mixed integer linear programming model integrating the cost and grey water footprint minimization was objectives applied to the problem.
- An improved, augmented ϵ -constraint method (Mavrotas and Florios, 2013) was applied to derive the tradeoff relationship between the cost and GWF objectives with three middle points (Mid 1, Mid 2, and Mid 3).
- Two approaches to determine the most preferred solution: (a) Imputed average cost of GWF, and (b) compromise solution method (Ramos et al., 2014).
- Total demand in the region assumed to be 250 million gallons of ethanol per year (MGY), with biorefinery capacity of 50 MGY or 100 MGY.
- Potential locations for the biorefineries were from TVA's industrial park database.
- Water pollution from mechanical operations and vehicle transportation was assumed to be negligible.

RESULTS

Per annum	TC Minimization	TGWF Minimization
Biorefinery site	Total 3 sites: 100-MGY \times 2 and 50-MGY \times 1	Total 6 sites: 50-MGY \times 6
TC	\$743 million	\$1,035 million
TGWF	-125 million m ³	-1,040 million m ³
NO ₃ ⁻ loadings leachate	Pre-land conversion: 2,292 Mg Post-land conversion: 1,144 Mg	Pre-land conversion: 10,232 Mg Post-land conversion: 1,198 Mg
Serving populations	301,277 residents	398,214 residents

Maps

Figure 3. Land conversion to switchgrass from other crops under different cases

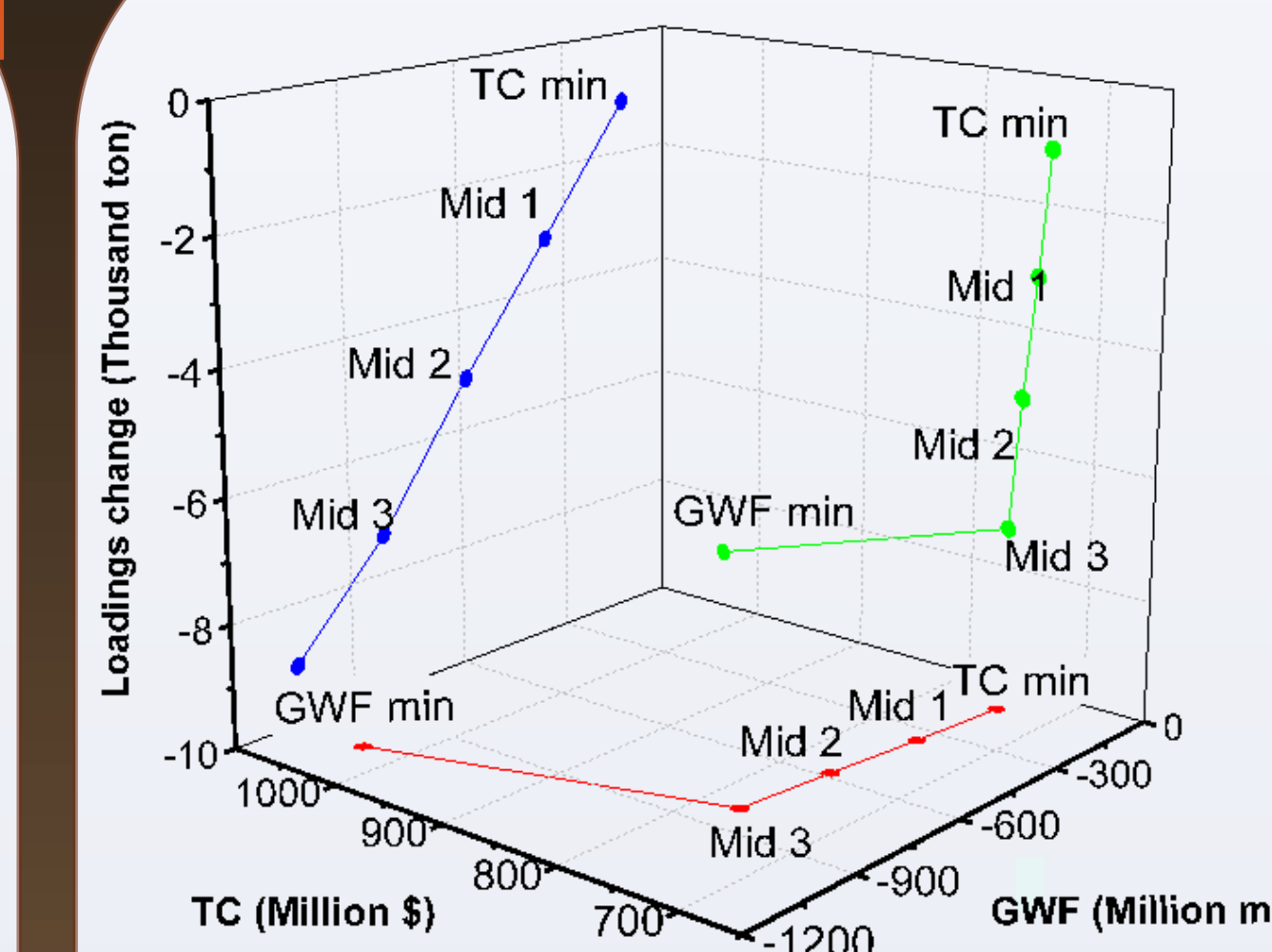
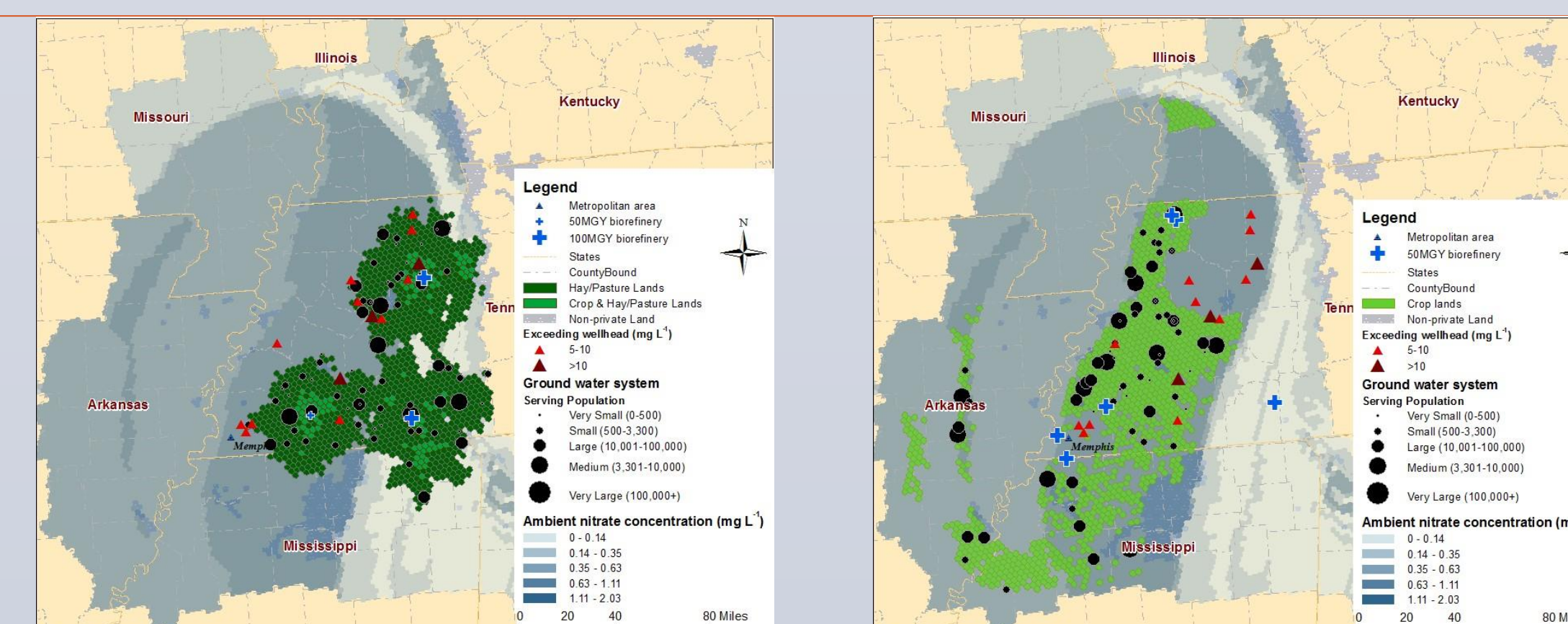


Figure 4. Tradeoff relationships between TC and GWF minimization, and corresponding nitrate loading

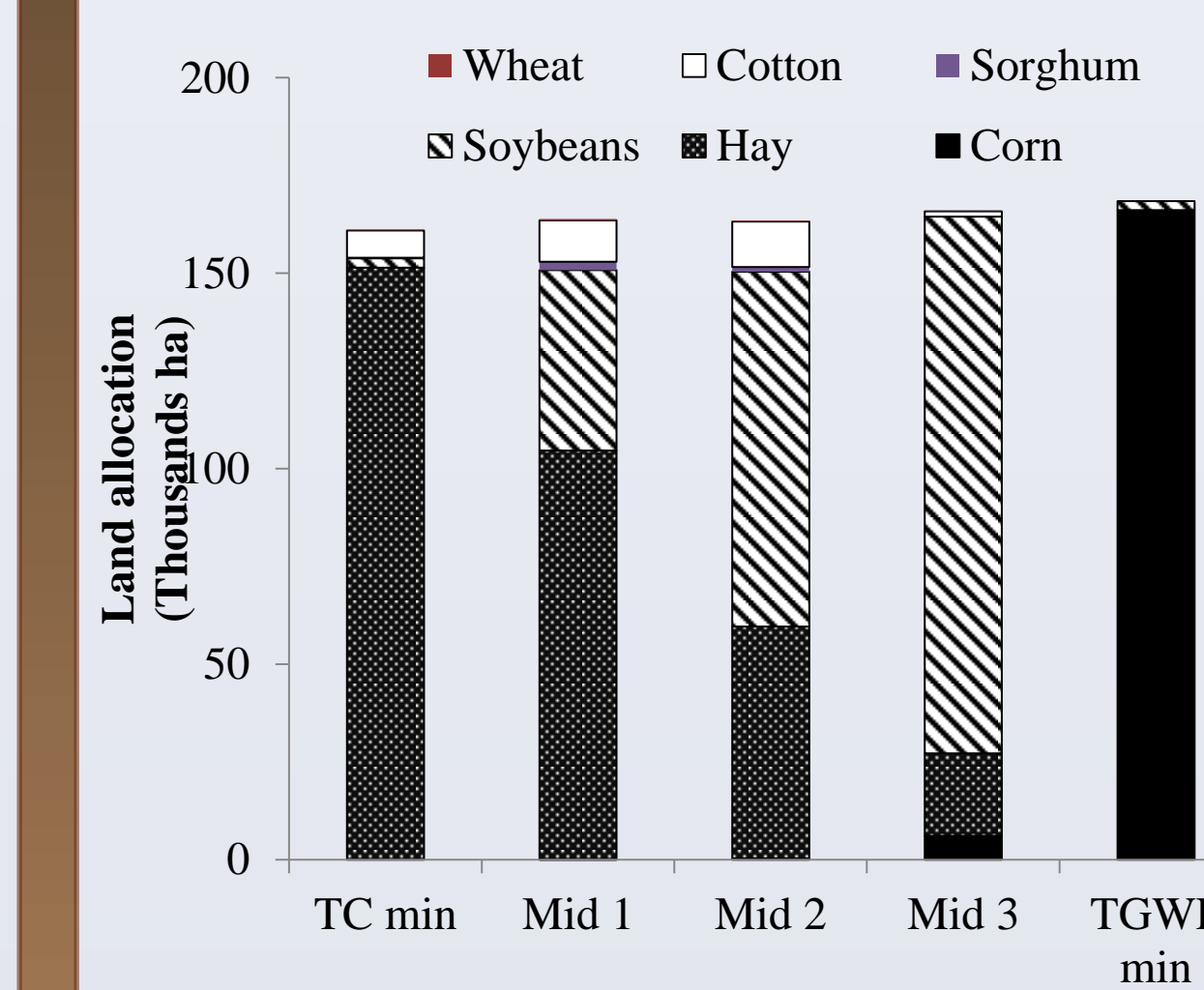


Figure 5. Land area allocation

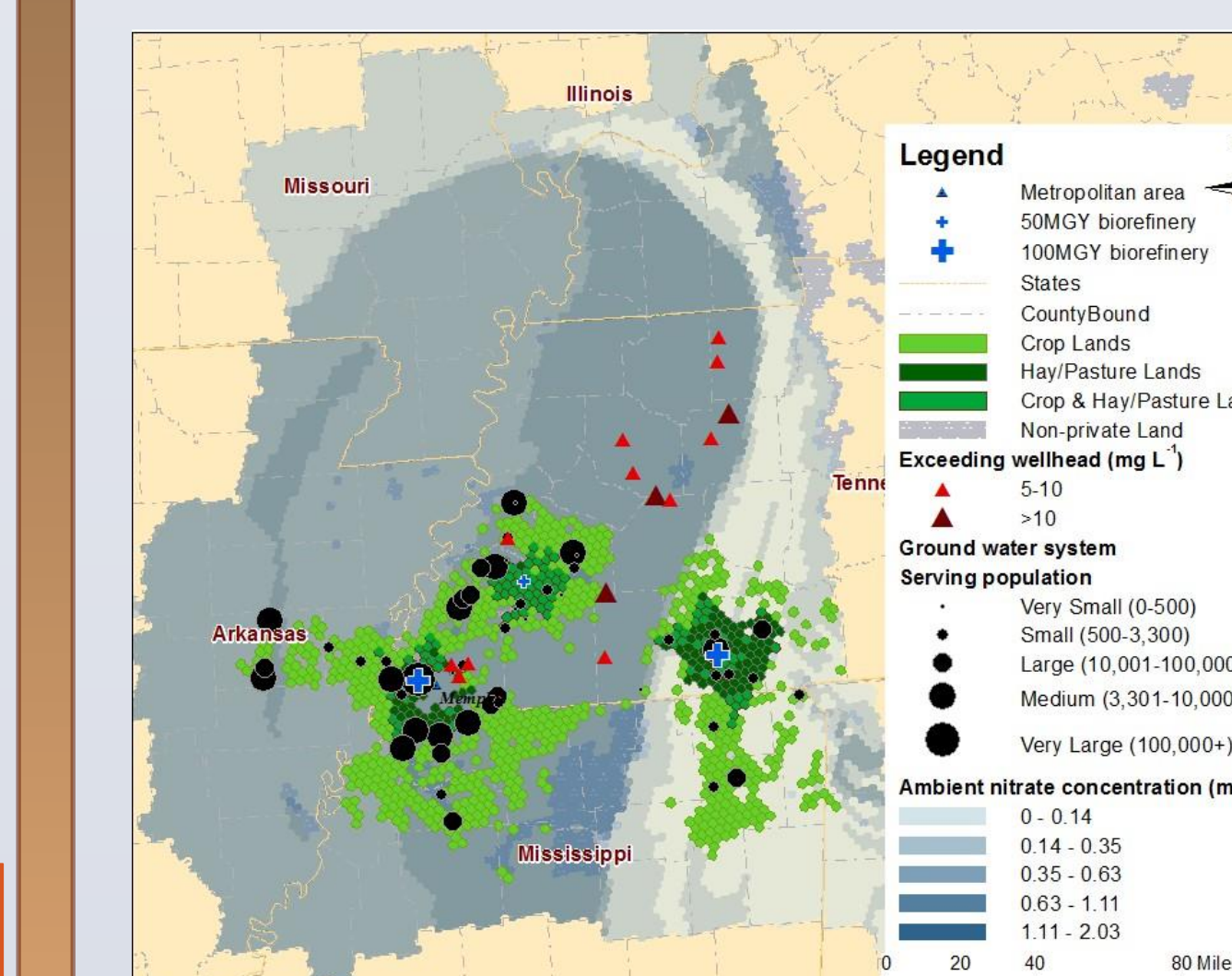


Figure 6. Most preferred solution with feedstock area

CONCLUSION

- Developing a switchgrass biofuel industry could approach to reduce nitrate-loadings to groundwater in west Tennessee although switchgrass supply chain is costly.
- Tradeoff between total feedstock cost and GWF in switchgrass supply chain was related to land selection for switchgrass production.
- The most preferred placement of switchgrass biofuel supply chain in west Tennessee could reduce grey water footprint by 811 thousand m³ and nitrate loadings by seven thousand tons in groundwater at cost of \$0.94/m³ GWF.

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