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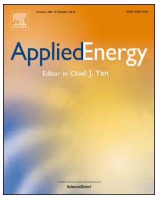

# Effect of land use change for bioenergy production on feedstock cost and water quality

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## HIGHLIGHTS

- Perennial switchgrass can reduce nitrate loadings and improve water quality.
- Multi-objective optimization is applied to spatial data for switchgrass supply.
- Average grey water footprint of switchgrass ranges 132–146 $\text{L L}^{-1}$ of ethanol.
- Tradeoffs between biomass costs and water quality are driven by land use changes.
- Cost of reducing grey water footprint in west Tennessee averages \$0.94 $\text{m}^{-3}$.

## ARTICLE INFO

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## ABSTRACT

Producing renewable fuel from dedicated energy crops, such as switchgrass, has the potential to generate localized environmental benefits. This study uses high-resolution spatial data for west Tennessee to quantify the effects of producing switchgrass for cellulosic ethanol on the grey water footprint (GWF), or the amount of freshwater needed to dilute nitrate leachate to a safe level, relative to existing agricultural production. In addition, the estimated cost and GWF are incorporated in a mixed-integer multi-objective optimization model to derive the efficient frontier of the feedstock supply chain and determine a switchgrass supply chain that achieves the greatest reduction in GWF at the lowest cost. Results suggest that background nitrate concentration in ambient water and the types of agricultural land converted to switchgrass production influence the extent of the GWF. The average GWF of switchgrass in the study area ranges between 131.8 $\text{L L}^{-1}$ and 145.9 $\text{L L}^{-1}$ of ethanol, which falls into the range of estimated GWF of other lignocellulosic biomass feedstock in the literature. Also, the average cost of reducing GWF from the feedstock supply chain identified by the compromise solution method is \$0.94 $\text{m}^{-3}$ in the region. A tradeoff between biofuel production costs and reduced nitrate loading in groundwater is driven by differences in the agricultural land converted to feedstock production. Our findings illustrate the energy-water-food nexus in the development of a local bioenergy sector and provide a management strategy associated with land use choices for the supply of energy crops. However, the water quality improvements associated with displacing crop with feedstock production in one region could be offset by expanded or more intensive agricultural production in other regions.

## 1. Introduction

The displacement of fossil fuel use with biofuel from renewable feedstock has the potential to reduce greenhouse gas emissions, stimulate rural economies, and generate localized environmental benefits. The Renewable Fuel Standard in the Energy Independence and Security Act of 2007 promotes the development of advanced biofuel that is produced from lignocellulosic biomass (e.g. perennial grasses crop and woody residues). Switchgrass (*Panicum virgatum* L.), a species native to North America, is a promising dedicated energy crop for biofuel production in the Southeastern states, including Tennessee [1,2]. Switchgrass has many advantages for biofuel production, including high

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*Abbreviations:* GWF, grey water footprint; EPA, environmental protection agency; MLY, million liters per year; MILP, mixed integer linear program

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biomass yield [3,4], climate and soils adaptability [5], and low fertilization requirements with high nutrient uptake efficiency [3,6]. Displacing croplands with switchgrass production for biofuel could improve local ecosystem performance by reducing water demand [7,8] and pollution pressure from fertilization [9–11], including reducing nitrate loadings to local groundwater aquifers and lowering the risk of groundwater contamination.

The effects on groundwater quality of converting land from crop to switchgrass production could be analyzed by examining differences in nitrate accumulation in groundwater over time in areas where land is used for feedstock instead of crop production. However, data on aquifer boundaries and volumes is scarce and the modeling needed to determine nitrate levels in groundwater aquifers over time is expensive. An alternative approach is to use the concept of *grey water footprint* (GWF) [12,13]. GWF is defined as the volume of freshwater needed to sufficiently dilute pollutant loadings to meet ambient water quality standards, given background pollutant concentration. The amount of groundwater needed to dilute the leachate from surface crop management could be considered an indicator of the degree of water pollution from aboveground activities [14]. Previous studies suggest that using water volume required for assimilating pollutants as an indicator of water pollution is superior to using the concentration of contaminants because the former approach brings water pollution into the same unit as consumptive use [14–16].

Water footprint estimation has become a popular way to assess the demands placed on water resources by economic activities since its appearance in Hoekstra and Hung [17]. Most water footprint analyses of food crops or bioenergy feedstock have focused on consumptive use of water, i.e., water that is incorporated in, or evaporates as part of, the production process. In these analyses, a distinction is often made between *blue water footprint* – fresh surface and groundwater – and *green water footprint* – rainwater stored in vegetation or the soil [13,18]. A number of studies have made a global estimate of the water footprint associated with different food crops and biofuel feedstock, and presented a wide range of estimates depending on the feedstock and location [13,19–21]. National-scale water footprint analyses suggest the biofuel policy and target could substantially increase the water footprint of feedstock production [e.g. 22–25]. Although groundwater has become an increasingly important water supply source [26], estimation of GWF for biofuel feedstock [15,27–31] has been relatively limited in water footprint analysis [29,32].

This study considers the possibility that incorporating both private costs and environmental benefits, in the form of reductions in nitrate loadings to groundwater, in the design of switchgrass supply chains could lead to more socially efficient designs. This study uses high-resolution spatial data in west Tennessee to quantify the effects of producing switchgrass for cellulosic ethanol on the GWF, or the amount of freshwater needed to dilute nitrate leachate to a safe level, relative to existing agricultural production. More specifically, the study addresses two questions. First, will the development of a regional switchgrass-based biofuel industry reduce the GWF associated with local agricultural (including biomass feedstock) production? Second, how much do the costs of feedstock production increase with reductions in local GWF generated by changes in the design of the feedstock supply chain?

Analyzing the effects of biofuel feedstock production on the local agricultural GWF contributes to the literature that has employed an increasing variety of environmental metrics to evaluate biomass or biofuel supply chains [e.g. 33–34]. The study's integration of mathematical model valuation and high-resolution geospatial data on the assessment of both economic costs and the GWF associated with biofuel feedstock production makes a novel contribution to this literature. The integration of private costs and GWF enables exposition of the relationship between private costs of biofuel industry, GWF reduction, and cropland use. Further, using high resolution spatial data in a biofuel feedstock supply chain model produces spatially explicit projections of the economic and environmental impacts of alternative supply chain designs and provides valuable information for stakeholders. It also addresses an area of emphasis for future research identified in prior water footprint research [32].

## 2. Study area

The State of Tennessee is one of a few U.S. states that have actively promoted the development of local bioenergy industries. The Tennessee Biofuels Initiative, established in 2007, is a state-supported program for growing the switchgrass-based bioenergy sector [35]. Thus, Tennessee is an appropriate venue for this analysis. West Tennessee, in particular, is selected as the study area as it: (i) contains most of the state's cropland and has great potential for switchgrass establishment given its productive soils and favorable climate, (ii) has high demand for transportation fuel as home to the state's second most populous metropolitan area (Memphis), and (iii) depends on groundwater aquifers for household water supply to nearly 96% of its residents [36]. The safety of the groundwater sources in west Tennessee for drinking water is inextricably linked to surface land use, groundwater quality, and hydraulic direction of groundwater flow in the karstic aquifers characteristic of the region [37]. The region's unconfined sand aquifers, vulnerable to contamination from aboveground activities, have been identified as critical issues for groundwater pollution prevention and management in the region [37].

The application of commercial fertilizers is the largest single nonpoint source of nutrient loading to groundwater and is responsible for low-oxygen levels and eutrophication in numerous groundwater bodies [38–40]. Fertilizer applications to low-nitrogen-uptake-efficiency crops result in excess nitrogen that runs off into surface waters, is retained in the soil, or leaches into groundwater. Households using domestic shallow wells near existing or former agricultural settings as sources of drinking water face elevated risks of Methemoglobinemia or "blue-baby syndrome" with elevated nitrate concentrations [38].

Nearly 0.8 million hectares (ha) in west Tennessee were used for crop production in 2015, which accounted for 33% of the total land area [41]. Elevated nitrate levels in shallow groundwater aquifers underlying agricultural and urban areas are common in west Tennessee due to human activities [42]. Between 1980 and 2014, three wells in west Tennessee exceeded the maximum contaminant level for nitrate (10 mg $L^{-1}$) out of 202 wells established by US Geological Survey Water Resources [43]. An additional 11 wells exceeded 5 mg $L^{-1}$ and required frequent water quality monitoring by the U.S. Environmental Protection Agency (EPA) (see Fig. 1) [44].

## 3. Methods and data

### 3.1. Switchgrass supply chain design and assumptions

The system boundaries for calculating the costs and GWF associated with the biofuel supply chain in this study extend from the farm to the conversion facility. The feedstock supply chain consists of six components: (i) land allocation, (ii) biomass production, (iii) biomass harvest, (iv) biomass storage, (v) biomass transportation, and (vi) conversion facility construction and operation. Switchgrass harvest is assumed to occur after senescence between November and February using square balers. Switchgrass can either be directly delivered to the conversion facility for biofuel production during the month harvested, or stored at the side of fields from which it is harvested. Stored switchgrass is transported to a conversion facility each month during the off-harvest season. Dry matter loss for the stored switchgrass (assuming protection with tarps and pallets) is based on the findings in Mooney et al. [45].

Annual biofuel production in west Tennessee is assumed to be 946 million L $year^{-1}$ (MLY) based on the assumption of replacing 20% of transportation fuel use in Tennessee along with the share of population