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Fine-Scale Analysis of the Energy−Land−Water Nexus: Nitrate Leaching Implications of Biomass Cofiring in the Midwestern United States

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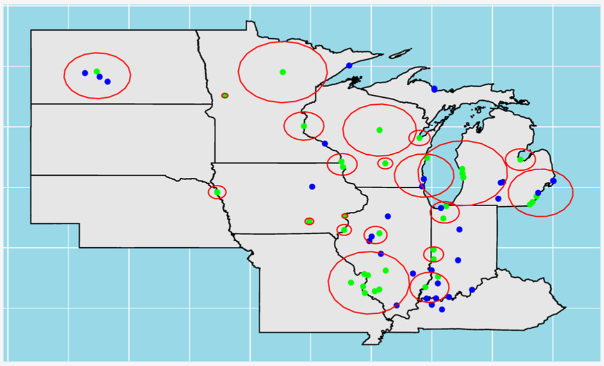

ABSTRACT: As scientists seek to better understand the linkages between energy, water, and land systems, they confront a critical question of scale for their analysis. Many studies exploring this nexus restrict themselves to a small area in order to capture fine-scale processes, whereas other studies focus on interactions between energy, water, and land over broader domains but apply coarse resolution methods. Detailed studies of a narrow domain can be misleading if the policy intervention considered is broad-based and has impacts on energy, land, and agricultural markets. Regional studies with aggregate low-resolution representations may miss critical feedbacks driven by the dynamic interactions between subsystems. This study applies a novel, gridded energy−land−water modeling system to analyze the local environmental impacts of biomass cofiring of coal power plants across the upper MISO region. We use this framework to examine the impacts of a hypothetical biomass cofiring technology mandate of coal-fired power plants using corn residues. We find that this scenario has a significant impact on land allocation, fertilizer applications, and nitrogen leaching. The effects also impact regions not involved in cofiring through agricultural markets. Further, some MISO coal-fired plants would cease generation because the competition for biomass increases the cost of this feedstock and because the higher operating costs of cofiring renders them uncompetitive with other generation sources. These factors are not captured by analyses undertaken at the level of an individual power plant. We also show that a region-wide analysis of this cofiring mandate would have registered only a modest increase in nitrate leaching (just +5% across the upper MISO region). Such aggregate analyses would have obscured the extremely large increases in leaching at particular locations, as much as +60%. Many of these locations are already pollution hotspots. Fine-scale analysis, nested within a broader framework, is necessary to capture these critical environmental interactions within the energy, land, and water nexus.

1. INTRODUCTION

Challenges at the intersection of energy and food production, environmental impacts, natural resources, and critical infrastructures are increasingly crossing not only disciplinary boundaries, but involve interactions across policy domains and natural and economic systems that have historically been studied independently. Growing out of several research communities, including the integrated assessment modeling groups studying climate change mitigation, adaptation, and impacts, there is increased focus on such intersections, including energy−water−land and other coupled system dynamics. These studies examine a broad range of issues including air quality, greenhouse gas emissions, water quality, water availability, as well as impacts on energy and food availability and prices.[1]

As the importance of cross-system interactions increases, a methodological question that arises concerns the appropriate scale and scope of analysis. The majority of studies in this space employ one of two approaches: (1) a high-level model or integrated framework of models that resolve multiple systems but at relatively coarse scale,[2] potentially including downscaled outcomes for key variables;[3] or (2) a model or empirical analysis with a finer scale resolution focused on the primary system of interest.[4−6] However, in some cases, it may be necessary to bridge these two approaches in order to capture the critical feedbacks across subsystems and across scales. Understanding when this is required and when these feedbacks can be neglected remains an open research question in the literature.

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To focus our discussion and provide a substantive example, we consider the inter-related environmental challenges of reducing greenhouse gas emissions from the electric power system via a hypothetical cofiring technology mandate for coal-fired power plants using corn residues, the potential role of biomass as a carbon-neutral fuel for electricity generation, and consequent impacts on land use and water quality. One type of analysis with a long tradition in this field involves projections of global or national scale emissions and energy use on annual time steps from models that resolve generation technologies by type but not individual units, in order to represent feedbacks with other systems; recent examples include global scenario projections by Grubler et al.,[7] projections of U.S. GHG emissions by Eshraghi et al.,[8] and scenarios for projections of U.S. emissions by Brown et al.[9] An alternative approach to estimating potential emissions reductions relies on data from historical observations, such as the analysis of plant-level emissions by Tong et al.,[10] and state-level empirical analyses of the emissions and technology impacts of state renewable portfolio standards (RPS) by Carley et al.[11] and Grant et al.;[12] these studies usually do not consider feedbacks with other related systems such as land or water. A third set of studies utilize detailed models with fine spatial and temporal resolution; for example, Sanchez et al.[13] performed a detailed study of the Western U.S. to show the role that biomass can play in reducing emissions from the electricity sector. Johnson and Novacheck[14] perform a similarly detailed study of the Midwest to project future emissions from extending the RPS for the State of Michigan. However, the feedbacks to local and regional land, water, and food systems from biomass and other fuels consumed are typically not resolved in these detailed plant-level analyses.

In this study, we present an example of a modeling framework with both fine-scale resolution and regional scope for multiple interacting systems to explore the consequences of mandating biomass cofiring in coal plants from Midwestern states to encourage use of biomass in power generation. We demonstrate that electric power sector carbon reductions from the hypothetical mandate come at the cost of induced land-use changes in agriculture that ultimately exacerbate water quality in a number of environmental hotspots in the region. More importantly, this example illustrates that the trade-offs between environmental impacts would not be apparent without a multisystem, multiscale framework capturing the feedbacks between energy, agricultural markets, land-use, and water quality at fine scale.

2. METHODS AND MODELS

2.1. Case Study: Biomass Cofiring for Coal Generation in Midwestern U.S. The research question for the analysis presented here is: what are the cross-system/cross-scale impacts of a technology mandate for coal-fired power plants in the Midwestern U.S. to cofire with biomass? This question is motivated by the confluence of many competing objectives for the electric power system in the U.S., including reductions in carbon emissions to address climate change, the absence of a coordinated national program for GHG emissions reductions, and financial pressures on coal generator owners from low electricity prices.

We select the Midwestern region for this case study because of the substantial quantity of coal-fired generation in the power system and the abundance of corn production, the residue from which offers a potential low-cost source of biomass supply, although its removal can create additional environmental challenges. A hypothetical biomass cofiring mandate across the Midwestern states could provide benefits to both coal generation owners and to corn farmers, and therefore it could present a compelling policy option, from a political—economy point of view. The portion of the U.S. electric system in this region is managed by the Midcontinent Independent System Operator (MISO). The MISO is organized as a single competitive wholesale electricity market for generation, through centrally coordinated auctions. For simplicity, we will refer to our study region as "MISO", even though this term specifically refers to the electricity market and the administrating institution.

As states look for ways to reduce carbon emissions from the energy sector, in addition to continued investment in wind and solar power, biomass provides an important potential alternative. Biomass cofiring (i.e., combustion of a mix of biomass and coal in the same boiler) is considered to be a promising way to complement other renewable sources of energy, but at a lower cost and higher efficiency compared with biomass-only power plants.[15] Due to its relatively low energy density, biomass feedstock is usually associated with high transportation costs. Consequently, the potential for cofiring at a given coal-fired power plant depends on the local availability of biomass. In the MISO region, the spatial distribution of biomass is very heterogeneous, with some areas able to provide a large quantity of local biomass feedstock, while in others there is less availability. To accurately investigate the cofiring potential of different coal plants in the MISO region, the heterogeneous spatial distribution of biomass must be considered.

Candidate feedstocks for large scale biomass cofiring in the United States include forestry residue, agricultural residue, and dedicated energy crops. In this study, we restrict our consideration to residue biomass because residues do not require dedicated croplands and are generally more economical.[16] While forestry residue is an attractive option in some regions, the availability of forestry residue in the MISO region is limited across most of the region and therefore cannot provide significant volumes of feedstock at a competitive cost. In contrast, the upper MISO region coincides with the U.S. Corn Belt and therefore offers a large quantity of agricultural residues.

Corn and soybeans are the dominant crops produced in this region, but only corn residue (typically termed corn stover) is suitable for cofiring. Demand for corn stover would result in an increased payoff for corn production in those areas where farmers can sell corn residue to nearby power plants. This, in turn, could induce cropland expansion as well as a shift toward continuous corn planting thereby resulting in increased vulnerability to pests and disease, as well as additional inorganic nitrogen fertilizer applications leading to greater potential for nitrogen leaching to the water system.[17] Removal of corn residue can also cause increased soil erosion and long-term yield decline and therefore requires commercial replacement of lost nutrients. This, in turn, limits the desirable residue harvest per hectare.[18−23]

Nitrate leaching is a significant source of water quality degradation in the Midwestern region of the U.S. as well as downstream, causing a range of hazards threatening biodiversity, crop yield, and human health.[24−26] Leakage of reactive nitrogen (N) from human activities causes significant economic loss nationwide.[27] The lost nutrients can be transported as far away as the Gulf of Mexico, where this has resulted in a hypoxic (low-oxygen) area often referred to as the "Dead Zone".[28] According to the U.S. Enviroonmental Protection Agency Hypoxia Task Force, the 2017 hypoxic zone measured 8776 square miles, and reducing this size to a more acceptable level by 2035 will require at least a 45% reduction in the N load exported by the Mississippi and Atchafalaya Rivers.

Any new development that increases the profitability of corn production is also likely to lead to cropland expansion, at least in the neighborhood of the cofiring power plant. While there is not yet sufficient experience with corn stover cofiring to estimate the spatial pattern of such expansion, much can be learned from the experience with ethanol plants in the Corn Belt. As with cofiring, ethanol production provides a new source of demand and increased local profitability for corn producers. Wright et al.[29] examine the consequences for cropland conversion stemming from the growth in ethanol plants across the United States over the 2008−2012 period. They estimate that 3.6 M acres of grasslands were converted to cropland within a 100 mile radius of the ethanol plants over this period. At the same time, outside this 100 mile radius there was evidence of reversion of cropland to grassland.

2.2. Integrated Modeling Framework: Overview. In order to estimate the local land use and water quality impacts of corn stover cofiring of coal power plants in the MISO region, we proceed in seven steps, as outlined in Figure 1, using four fine-scale resolution models: the Power System Scheduling and Dispatch Model, the Supply Circle Model, the SIMPLE-G Model, and the Agro-IBIS Model. (1) We use the Power System Scheduling and Dispatch Model to identify and locate all individual coal-fired generators across the upper MISO region and estimate the demand of biomass for each power plant. (2) We use the Supply Circle model to measure the local availability of biomass at different levels of cost and estimate a unique biomass supply function for each power plant. (3) We use a production cost model of the power system to determine the operation of cofired plants within the electricity market, and the interaction of this model with the plant-specific biomass supply functions to determine the equilibrium pattern of power generation and biomass demand for a given level of cofiring mandate. (4) Based on the equilibrium demands and spatial distributions of biomass, we identify supply zones of biomass around each power plant, which are the regions required by the power plants to collect enough biomass given a cofiring requirement. (5) In the first round of estimation, there is overlap among supply zones for many individual power plants, we therefore introduce competition for biomass by combining overlapping supply zones. This results in a new, updated equilibrium set of biomass demand and supply outcomes (iterating from step 1 to step 5). (More detailed information about this solution procedure is provided in the Supporting Information (SI).) (6) In order to draw out the implications for cropland use and water quality, we draw on estimated transfer functions describing the gridded response of crop growth and nitrate leaching to additional nitrogen fertilizer applications based on Agro-IBIS agro-ecosystem model. This information is integrated into the gridded (5 arc minute within the U.S.) version of SIMPLE (a Simplified International Model of Prices Land-use and the Environment). (7) Using this parametrized, gridded version of SIMPLE-G, we simulate the impacts of the additional revenue from collecting biomass within the supply zones on land use, nitrogen fertilizer applications, and nitrate leaching in water system.

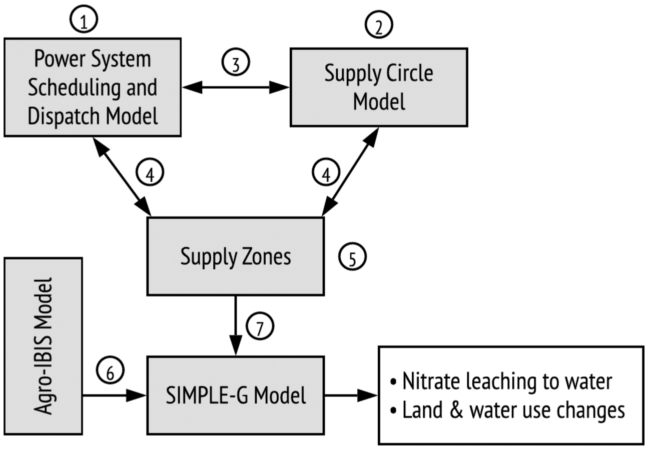


Figure 1. Linkages between the dynamically applied models and associated objectives. Boxes correspond to models employed in this nexus analysis and numbers correspond to individual steps as discussed in the text.

Although we describe the sequence of steps to clarify the analysis process, it is important to highlight that the feedbacks between the four models are captured in our framework. For instance, step 3 is achieved by iterating between the power and land use system models. This linkage is illustrated in detail in SI Figure S2, where the equilibrium among both models is obtained via an iterative process. Similarly, the supply circle model and SIMPLE-G are inextricably interwoven as the availability of corn residue depends on the existing distribution of corn production across the landscape. Both models share this common input, and it is this spatial distribution of production that determines the residue supply curves available to the power plants.

2.3. Identifying Candidate Coal Plants Across the Upper MISO Region. There were 72 operational (as of 2016) coal-fired plants that are considered to be candidates for cofiring within the upper MISO region. As we describe in Section 2.5, we simulate three scenarios from the power systems model: reference, carbon tax only, and cofire mandate scenarios to be described in more detail below.

2.4. Supply Circle Model. Feedstock cost represents the variable cost of biomass cofiring, which consists of harvest cost and transportation cost.[30,16] Due to the low energy density of corn stover, the transportation costs rapidly increase with the distance between the harvest location and the power plant location. Power plants located in areas with greater availability of local biomass are expected to pay lower transportation costs compared with power plants located in areas with lower crop density. Because of the strong dependence of biomass cost on distance from the plant, the variability in local crop density, and the variation in capacity of different plants, there is significant variation in the plant-specific feedstock costs. Representing this variation is critical in determining the ultimate demand for biomass and therefore the impacts.

To capture the heterogeneous distribution of biomass across the upper MISO region, we measure the available quantity of biomass within a set of concentric supply zones around each coal plant. For simplicity, we assume symmetric zones of constant radius, but estimate the heterogeneous supply

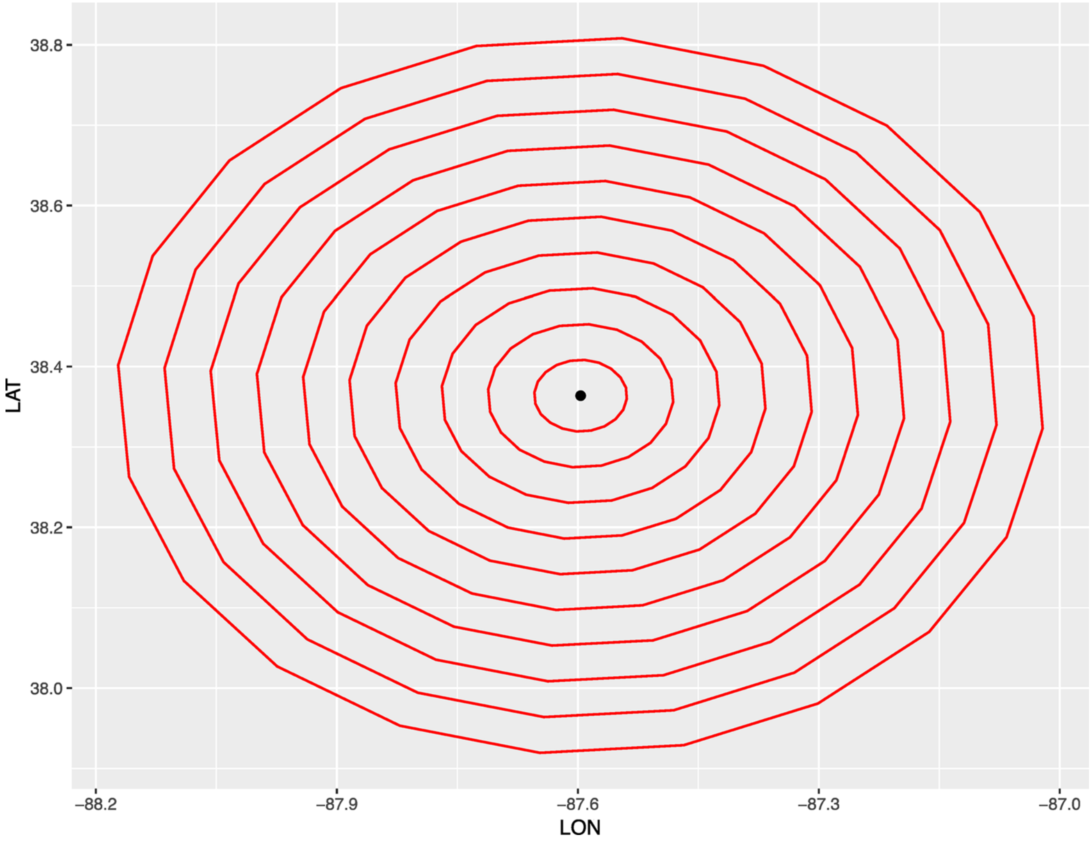


Figure 2. Biomass supply zones around a representative power plant (black dot in the center). Each circle has 5 km radius increments away from the center, the location of the power plant, therefore, bears longer transportation distance and higher transportation cost. Biomass quantity is calculated in each supply zone bounded by each circle. For each power plant, 80 circles, therefore 80 supply zones, have been identified.

quantity within each circular region as described below. Specifically, we construct a set of 80 potential zones around each power plant in 5 km radius increments (Figure 2) and calculate the total quantity of available biomass within each zone. The feedstock cost for biomass within each zone is the total cost of harvesting and transporting biomass from the outer boundary of the zone, the furthest locations with the highest transportation cost. This provides a large set of biomass quantity and cost pairs with which we estimate a unique, nonlinear biomass supply function for each power plant (see SI).

We use the Cropland Data Layer data set (CDL) from the United States Department of Agriculture for 2010 to measure the total available quantity of corn residue within each supply zone. CDL data specifies the crops planted on each grid cell (30 m × 30 m) and the location of the grid cell. We aggregate the land area within all corn grid cells and calculate the total production area of corn within each zone. County level yield data for corn are from the calculation implemented by Haqiqi and Hertel[31] and based on methods from Schlenker and Roberts.[32] Using yield data for corn, with 0.0237 dry ton of corn residue corresponding to 1 bushel of corn,[16] and assuming a sustainable residue removal rate of 33% (Thompson and Tyner 2014), we calculate the total quantity of corn residue available for cofiring within each supply zone. The feedstock cost of corn residue includes harvest cost and transportation cost. We obtain harvest cost from Thompson and Tyner (2014), which includes equipment cost, labor cost, fuel cost, wrap cost, and the cost to replace the nutrients removed with the residue. Transportation cost data are from the DOE Billion-Ton Report (2016), which include fixed logistic costs (these do not depend on transportation distance) and variable transportation costs that vary with distance, loaded and unloaded cost per mile, and time cost. Detailed data sources for harvest and transport costs are provided in SI Table S1.

The calculated feedstock cost is the sum of harvest and transportation cost for the biomass harvested at the boundary of each zone and represents the highest cost within that zone. As a result, this can be considered the marginal cost of supply within that zone. The plant-specific, nonlinear supply function is assumed to be quadratic in price, as eq 1:

$$\text{quantity} = \beta_0 + \beta_1 \times \text{price} + \beta_2 \times \text{price}^2 \qquad (1)$$

With the estimated supply function for corn residue for each power plant (see SI Table S2 for the estimated coefficients for these functions), we are able to identify the available quantity of corn residue for each power plant at any given price level, and equivalently can determine the price (cost) of biomass for any demanded quantity at that location.

2.5. Power System Scheduling and Dispatch Model.

To represent the operations of cofired coal plants, and thereby determine the quantity of biomass consumed, it is necessary to model the entire power system because different generation sources compete in the electricity market. The present study focuses on the upper MISO region, which comprises 10 states in the U.S.: Iowa (IA), Illinois (IL), Indiana (IN), Kentucky (KY), Michigan (MI), Minnesota (MN), Missouri (MO), North Dakota (ND), South Dakota (SD), and Wisconsin

(WI). Electric power within MISO is provided through a competitive wholesale generation market, in which generators offer bids into daily auctions for scheduling the next day's power, supplemented with frequent intraday auctions for adjustments to generation to maintain the supply demand balance. In general, the marginal cost of the generator that clears the market for a given auction sets the price at which all units are paid. If a coal plant is augmented with biomass cofiring capability, thereby increasing its marginal production cost, this will likely change the number of hours per year that it operates. Further, because of operational constraints such as startup lag times, startup costs, and nonzero minimum output levels, coal units need to be economic for a sufficient number of chronological hours, or it will not be brought online at all.

To correctly account for these constraints and provide an estimate of the demand for biomass from cofiring, we apply a unit commitment (UC) model, which solves for the minimum cost schedule (ON/OFF status), and dispatch (energy production) for all generators over the time horizon. UC models are typically formulated as mixed integer linear programming (MILP) models, and include operational constraints for each generator, such as minimum and maximum output, ramping limits, and minimum number of hours that a plant can be online (or offline) after a startup (or shutdown). We use the UC formulation from Morales-Espana et al.[33] The objective function of the UC model minimizes the total operational costs, eq 2. It depends on three components: the total variable operational cost, the start-up cost (fixed and fuel cost), and the cost of nonserved energy. The nomenclature and detailed mathematical formulation are provided in the SI.

$$\begin{aligned}\text{vTotalcost} = {} & \sum_{\text{egu,h}} [\text{vGen(egu, h)} \times \text{pOpcost(egu)} + \text{pTurnonfuelcost(egu)} \times \text{vTurnondecision(egu, h)}] \\ & + \sum_{\text{egu,h}} [\text{pStartupfixedcost(egu)} \times \text{vTurnondecision(egu, h)}] + \sum_{\text{h}} [\text{vNse(h)} \times \text{scCnse}]\end{aligned} \qquad (2)$$

The model simulates an entire year by solving 52 one-week (168 h) segments using historical demand, wind generation, and solar generation from 2016 obtained from MISO.[34,35] The parameters for individual generators are obtained from the Emissions & Generation Resource Integrated Database[36] maintained by the United States Environmental Protection Agency. The model has 2974 generators of which 160 are coal generators, aggregated within 72 coal plants. We have extended the UC formulation to represent biomass cofiring technology. For simplicity, we assume that, when a coal plant cofires, all its generators participate in the biomass cofiring. The simulation of a cofiring mandate requires two additional elements in this version of the model: an incentive for cofiring and an additional constraint for coal plants. To create an incentive for cofiring, we assume a \$100 per ton carbon price is applied across all generators. This carbon price is modeled as a penalty in the UC model; hence, it affects eq 2. We then also assume that all coal plants must meet a constraint that coal-plants cofire at a 15% rate. We chose the 15% rate as it is technologically achievable with existing technology and does not require extensive capital investments in the coal plant. Higher levels of cofiring require significant capital costs, and increase the cost of cofiring dramatically. For clarity, we present results by comparing three alternative scenarios: a "Reference" case with no carbon tax and no cofiring mandate, a "Carbon Tax" case which only imposes the carbon tax but no cofiring requirement, and a "Cofire Mandate" case, which assumes both a carbon tax and that all coal plants cofire at a 15% rate.

Although individual plant level decisions do not affect coal and natural gas prices in fuel markets, the localized nature of agricultural residue makes the fuel cost and consumption within each supply circle interdependent. We therefore iterate between the power system scheduling and dispatch model and the supply circle model to find the equilibrium biomass price and demand for each coal generator (SI Figures S2 and S3).

A critical assumption in this study is that all the coal plants that generate electricity must cofire. This contrasts with the case of a renewable portfolio standard (RPS) wherein the decision to adopt cofiring by an individual plant is an equilibrium result in a game-theoretic sense, with all coal plants as profit-maximizing players. This requires a different, more computationally intense, solution method which is overly burdensome for this multisystem analysis. We will pursue this avenue in a separate study, favoring the simpler mandate scenario to allow exploration of the coupled systems aspects of this problem.

2.6. Agro-Ecological Model of Crop Production and Nitrate Leaching (Agro-IBIS). In this study, we used Agro-IBIS, an advanced version of the IBIS biosphere model[37] to characterize crop response to nitrogen fertilizer as well as nitrate leaching, both of which vary according to the level of fertilizer applied per hectare, as well as soils, weather, and cropping practice. Agro-IBIS was developed by adapting version 2.6 of the global IBIS model to explicitly model corn, soybean, and wheat crop systems as well as forests and grasslands.[37−40] Agro-IBIS simulates the movement of water, energy, momentum, carbon (C), and nitrogen (N), and the soil−plant−atmosphere system. The structure of Agro-IBIS has been previously described in detail,[37,41,42] and has been validated at the field scale,[37,41,42] including several AmeriFlux sites for coupled C and water cycling,[39,43,44] and the Mississippi basin-wide scale for yields, NO_3 leaching, soil moisture, ET, phenology, and net primary production.[40,42,45] Previous work at the Mississippi basin-wide scale has demonstrated the trade-offs between N usage, leaching to groundwater, crop yields,[38,45] and N transport to the Gulf of Mexico as impacted by the U.S. Renewable Fuel Standard and planting of dedicated bioenergy crops.[40,46,47]

Agro-IBIS accounts for agricultural management and the effects of environmental stressors on crop development and water balance and uses a 1 h time-step. At a continuum of horizontal grid resolutions from 5 m to 250 km, Agro-IBIS simulates optimal planting date, crop yields, water balance, and nitrate leaching; crop yield and nitrate leaching response to varied N-fertilizer applications; and yield response to climate change. Besides modeling short time scale carbon, nitrogen and water balance, and vegetation structure, Agro-IBIS simulates crop transitions through key phenological stages during development (emergence, grain fill, senescence), characterizes seasonal shifts in carbon allocation to specific crop carbon pools (i.e., leaf, stem, root, and grain), and quantifies nitrogen fixation (Kucharik and Brye 2003).

The model uses algorithms based on 10-day running mean maximum and minimum temperatures to determine the optimal planting date for corn, soybeans, and spring and winter wheat in each grid cell (Kucharik and Brye, 2003). Another algorithm uses the average number of growing degree days (GDD) accumulated during the period from April through September (base 0 °C for wheat, 8 °C for corn, and 10 °C for soybean) for the previous 5 years of climate data to choose a generic hybrid for planting; these hybrids vary solely in the number of GDD that are needed to reach flowering, silking, heading, and physiological maturity. Canopy and land surface processes in Agro-IBIS are based on the key differences in C3 and C4 crop physiology, daily phenology, and carbon allocation so coupled carbon−water exchange is responsive to agricultural management (e.g., irrigation, fertilizer application, planting date) and environmental stresses (e.g., climate, and water and nitrogen limitations) (Kucharik and Brye 2003, Ref 38).

By running Agro-IBIS thousands of times and fitting transfer functions to the resulting data, we have obtained grid-cell specific, nonlinear relationships between N applied and crop growth, as well as N leaching. These functions are directly incorporated into the gridded economic model.

2.7. Gridded Version of Simplified International Model of Prices Land-Use and the Environment Model (SIMPLE). Although the decision to supply biomass for cofiring is made by individual producers, macro-scale factors such as the prices of energy, crops, and agricultural inputs shape the decision-making environment facing individual agricultural producers. And farm-level decisions, when aggregated across the nation's largest corn and soy producing region, are likely to feed back to market prices, thereby requiring a national or even global modeling approach. To capture these local-global linkages, as well as to explore the implications of producer decisions for local environmental quality, we employ the SIMPLE-G-US-CS model. It is a gridded version of the SIMPLE model[48] that has been applied to analyzing a variety of sustainability issues related to agriculture.[49] The gridded version of SIMPLE, dubbed SIMPLE-G, obtains regional agricultural output and input usage via aggregation of grid-cell responses, thereby capturing the spatial heterogeneity inherent in agroecosystems.[50] Several versions have been developed that feature different spatial resolutions, crop aggregations, and agricultural production technologies. The version used in this study focuses on the continental United States and models the composite supply and demand for two major crops: corn and soybeans; hence, the US-CS at the end of SIMPLE-G-US-CS. The SI provide a more detailed description of the model structure and baseline data, as well as calibration and validation over the period: 1991−2010.

Large-scale biomass cofiring using corn stover can alter crop production and the environment in a variety of ways and SIMPLE-G-US-CS seeks to capture these responses. First, farmers within supply zones are likely to increase corn production due to the added revenues per acre cultivated (from selling corn stover). Given that corn is among the most intensive users of N fertilizer, growing more corn will increase N fertilizer applications and nitrate leaching. In addition to this direct effect, nitrate leaching can increase indirectly as a consequence of harvesting of corn stover since the presence of corn residue serves as a natural defense against soil erosion and nutrient loss.[18] Furthermore, the nitrogen embedded in the corn stover, after being removed from the field, must be replaced by commercial fertilizer.[17] This can lead to more N fertilizer applications and increased risk of nitrate leaching.[23] In order to capture these potential environmental impacts related to corn stover removal, three different sets of perturbations are applied to the grid-cells located within supply zones. The first involves a positive increment to corn revenues (Figure 6). Since the residue is produced in fixed proportion with the corn grain, this is equivalent to providing a subsidy to encourage more production of corn. Because the transportation cost of corn stover increases with distance, revenue gains are highest at the center of a supply zone, close to the demand source (power plants), and gradually decline as one moves toward the outer edge of the zone at which point transport costs offset all of the added revenue. The increase in revenue in the neighborhood of the power plants could reach \$25/dry ton of residue delivered. A second environmental impact from cofiring is captured via a shift in the leaching function, reflecting the increased propensity for nitrate leaching in the presence of diminished crop residue cover. As a consequence, for the same level of N application, the leaching rate (kg of nitrate leaching per hectare) rises by 7−13%, depending on the location and local practices. Finally, the nutrient replacement effect is captured via a shift in the N fertilizer yield function. The nutrient applied as replacement increases baseline N application rates by between 5 and 20% of initial applications. More information about the experimental design can be found in the SI. When confronted with these three shocks, the SIMPLE-G model iterates to a new equilibrium, with a new pattern of corn production and new equilibrium prices for corn and nitrogen fertilizer.

3. RESULTS

3.1. Implications of Cofiring for Plant Utilization. The resulting operations of the coal plants in MISO are illustrated in Figure 3 which reports the capacity factors across the region for the reference, carbon tax only, and cofire mandate scenarios. The capacity factor is defined as the total generation over the year as a fraction of the maximum possible generation from that unit (i.e., running at full capacity every hour of the year). A \$100 per ton carbon tax alone would make the vast majority of the coal plants too expensive to operate, with two-thirds of the plants showing capacity factors of less than 40% for the year. When a 15% cofiring mandate is imposed along with the carbon tax, the share of coal plants with less than a 40% capacity factor falls to 56%, and 14% of the plants operate with capacity factors above 60% (SI Table S3). As a point of reference, in the baseline case, 25 of the plants have capacity factors below 40%; in reality many of these plants are currently financially stressed, and some of these have since been retired or in the process of retirement.

Note that a coarse-scale model that did not resolve individual plants and hourly operations would likely have assumed much greater levels of generation, and therefore overestimated the amount of biomass demand. For example, an off-line calculation using the annual generation of coal plants from the reference case using historical data would have estimated an annual demand of 30 M tons of biomass demand, but explicitly solving for dispatch under the new operational costs results in just 10 M tons of biomass demand for cofiring.

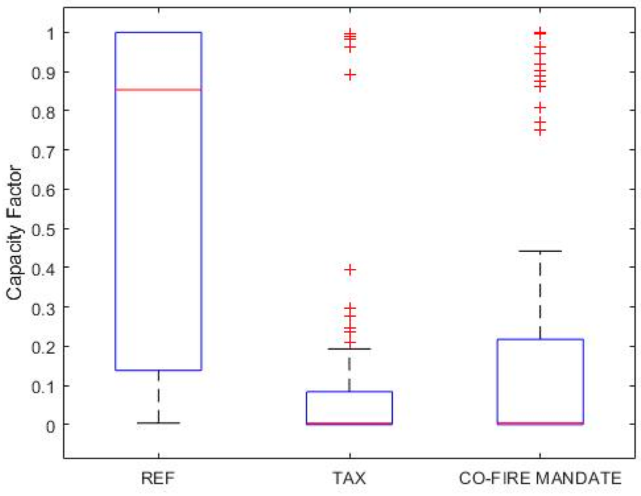


Figure 3. Capacity factors of all coal plants in MISO. Boxes enclose 50% of the data, red lines indicate medians, and whiskers encompass 90% of the plants. Outliers are marked with "+". In the baseline, half of the coal units have more than 80% utilization, but 25% have less than 20% utilization and are financially distressed.

The differential impacts of the higher cost of generation across individual coal plants further increases the spatial heterogeneity of the biomass demand. The final equilibrium supply zones for aggregate groups plants are shown in Figure 4.

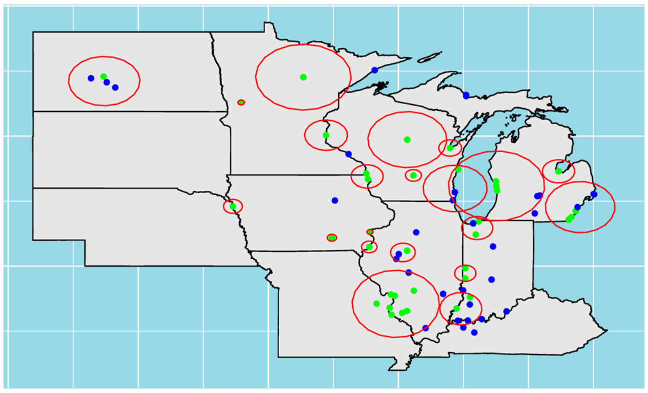


Figure 4. Coal-fired plants and the associated corn stover supply zones across the upper MISO region. Black lines delineate state boundaries; Green dots indicate coal-firing power plants; blue dots indicate plants that retire in the face of the mandate; red circles define unified supply zones. Note that 34 of the 72 plants do not generate power under the 15% cofiring rule (cofire mandate case), so these do not contribute to corn stover demand.

In the reference scenario, all the 72 coal plants in our model generate electricity. Based on historically observed generation (Emissions & Generation Resource Integrated Database (eGRID), 2016), just 1 out of 72 plants did not generate any electricity in 2016. Further, in the reference scenario, there are 6 out of 72 plants that have a capacity factor of 4% or lower. As a rule of thumb, it seems reasonable to assume that plants with 4% or lower capacity factor are running uneconomically. Using this criterion, six plants would shut down in the reference scenario and 43 plants would shut down in the cofire mandate scenario, which implies that 37 plants would not generate under a mandate, as compared to this modified baseline.

To demonstrate the value of modeling competition between plants in both the electricty and agricultural markets, we present an illustrative example focusing our analysis on a group of eight plants. We run the cofire mandate scenario assuming that each coal plant is the only one cofiring in the system; that is, cofiring one at a time, and compare these results with the cofire mandate scenario when all the coal plants in MISO are cofiring and therefore competing for biomass. Figure 5 shows the results of both scenarios.

Note that simulating each plant one at a time would overestimate the biomass demand and the spatial extent of the supply circle; that is, seven out of eight plants cofire. Representing the power system as a whole captures the spatial competition for biomass in the agricultural market, the effect of that competition on fuel supply and fuel costs on each generator, and the competition to produce electricity in the power sector. This spatial competition leads to higher biomass costs, and therefore and cofiring actually would occur; that is, two out of eight plants cofire.

3.2. Implications for Corn Production and Nitrate Leaching.

Figure 6 reports the predicted increase in revenues for farmers in each grid cell. From the perspective of power plants, the highest price they must pay for corn stover is the marginal cost of acquiring the last unit of feedstock; from the perspective of farmers, the lowest price they accept is the price that can cover all harvest cost and transportation cost of corn residue. Assuming the "law of one price" prevails for stover delivered to the power plant gate, and considering that the price received by farmers must cover the harvest and transportation costs of the last unit of corn residue needed by power plants, this results in additional revenues for the infra-marginal farms, with rents rising as we approach the power plant where transport costs fall toward zero. Heterogeneity of revenue also shows up across supply zones due to varying densities of corn production around the power plants; while some zones see small increases in revenue, revenue increases in other zones are relatively substantial. The heterogeneities both inside and across supply zones can be readily seen from Figure 6.

Figure 7 presents the predicted long run changes in corn production and nitrate leaching in both absolute and percentage terms. Not surprisingly, corn output increases within supply zones, incentivized by the additional revenue from selling crop residue. The growth is more pronounced in southern Illinois where the generation from cofiring is high, as is the density of corn production. Crop output outside of the supply zones falls slightly (Figure 7, a1). This follows from the higher fertilizer prices due to the increased demand, as well as the decline in corn grain prices because of increased corn production within these supply zones. The percentage change in corn output (Figure 7, a1) closely follows the pattern of added revenues in Figure 6. At the center of supply zones, corn production is predicted to increase by the largest amount, gradually declining to zero at the outer edge of the supply zones.

Implications for Nitrate Leaching. The most striking result is the large (25−45%) increase in nitrate leaching, comparted to the baseline, within the supply zones (Figure 7, b2). This change is partially explained by the N fertilizer intensification, that is, higher fertilizer application rates to boost crop yields and therefore stover. As soil approaches a state of nitrogen saturation (e.g., the soil matrix contains more available N than can be taken up by plants at any particular moment), the

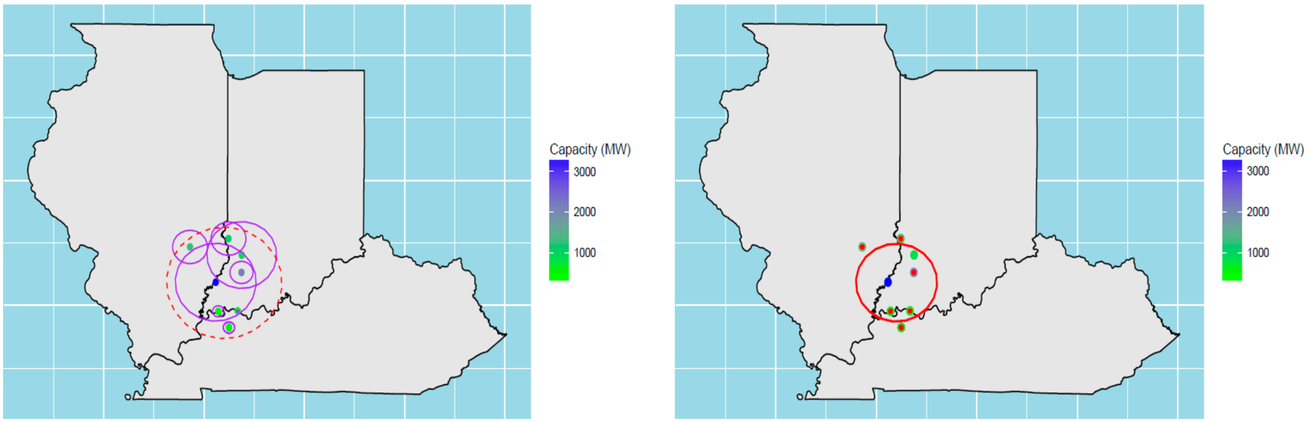


Figure 5. Biomass supply region when power plants cofire one at a time without spatial competition (left) vs all power plants cofire with spatial competition (right). The purple circles indicate the supply zones of individual plants in the group (left), and the red circles indicate the supply zone of the whole group (dashed red circle in the left graph is larger than the red circle in the right graph due to greater generation). The red dots in the right figure indicate the plants that do not generate under spatial competition.

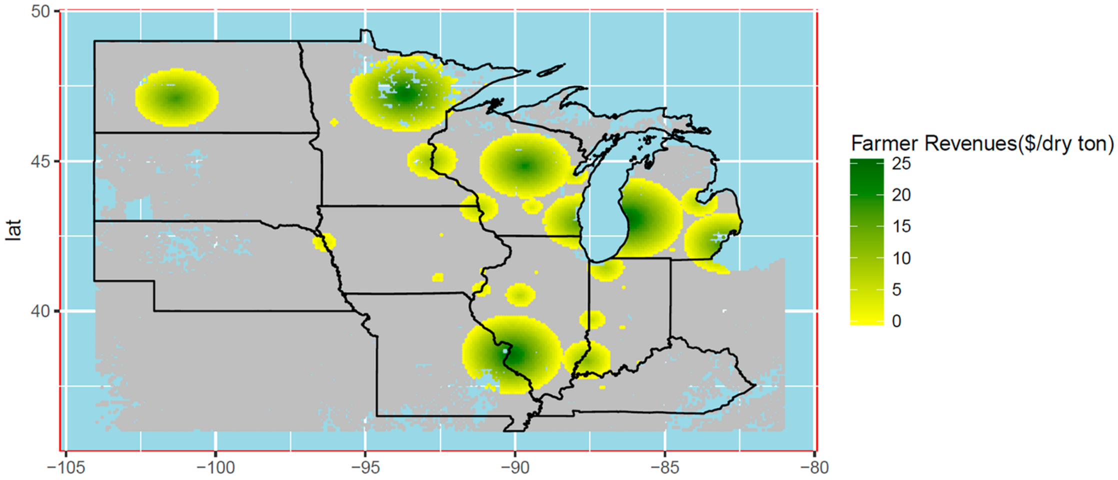


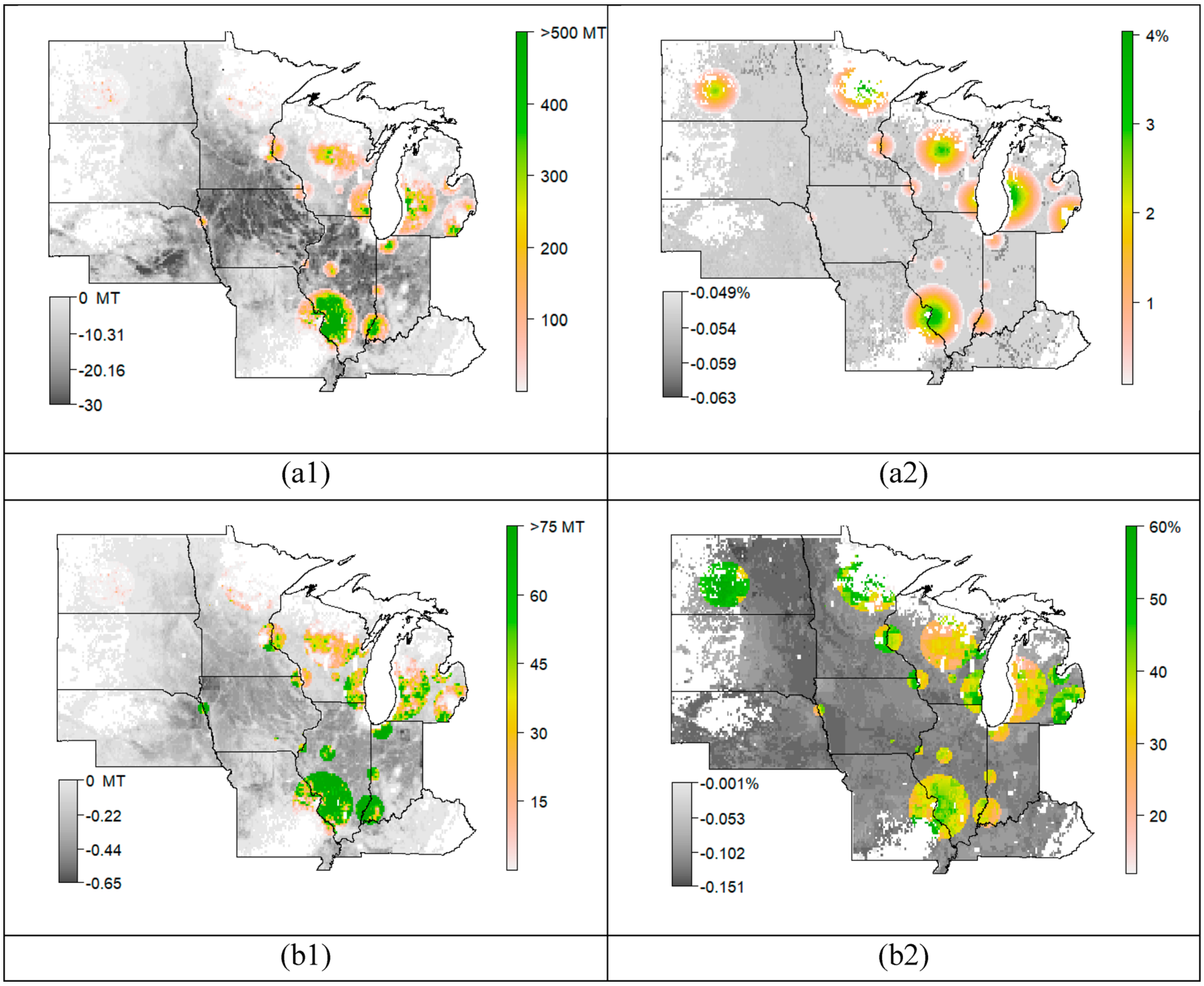
Figure 6. Impact of cofiring mandate on producer revenues inside supply zones (change in revenues, unit is $/dry ton of residue delivered). Demand for corn stover by cofiring power plants in the upper MISO region creates an added source of revenue for corn producers within the supply zones. This encourages expansion of corn production as well as intensification to generate more biomass supply.

impact of increased N fertilizer on yield diminishes, whereas the likelihood of N loss from leaching can increase exponentially. Therefore, overapplication of inorganic N fertilizer benefits crop yields only marginally, but the likelihood for N leaching could increase significantly as the key trade-off. More substantially, the increased leaching rate and load are attributed to N replacement for the removed corn stover. Nitrogen that is mineralized through soil organic matter and stover decomposition is a continuous and gradual process, as opposed to the typical instantaneous and broadcast application of inorganic fertilizer. These pulse inputs of fertilizer are more prone to leaching losses given the large N amount that is available in the crop root zone. This results in a higher likelihood of leaching with rainfall. Therefore, a potentially large amount of N leaching can occur with relatively small amounts of additional N fertilizer.

Another significant finding is the sharp contrast in the N leaching outcomes between local and regional spatial scales. For example, although the aggregate nitrate leaching across the upper MISO region increases by only 4.6% under the cofiring scenario, the local impacts on water quality are much more dramatic in key locations. Nitrate leaching increases by 40−60% relative to baseline in many areas that are in, or adjacent to, potential hotspots of nitrate pollution.[51] These results clearly demonstrate the value of fine-scale spatial analysis to the study of the energy−land−water nexus.

4. DISCUSSION

As scientists seek to better understand the linkages between energy, water, and land systems, they confront a critical question of scale for their analysis. Indeed, many researchers exploring this nexus restrict themselves to a small area, such as a single watershed or an individual power plant, in order to ensure that they can accurately capture local processes.[5,52] While such studies provide important scientific insights, if the impacts from a policy intervention are extrapolated to a regional or national scale on the basis of unit-level analyses, the critical aggregate impacts on energy, land, and agricultural markets and systems may either be missed or overestimated. Indeed, this is the case with the cofire mandate scenario considered in this paper. We find that spatial competition results in 46% of the coal-fired plants in the upper-MISO region ceasing generation of electricity instead of cofiring biomass at the 15% level, and the capacity factor of other plants falls in many cases. Ignoring these interactions in the



(a1) (a2)

(b1) (b2)

Figure 7. Quantity (a1) and percentage (a2) changes in corn production, as well as quantity (b1) and percentage (b2) changes in nitrate leaching caused by biomass cofiring in the upper MISO region (cofire mandate scenario). All quantity changes are in metric tons (MT) per 5 arc-minute grid cell. Inside and outside supply zone changes are presented in different color scales because the off-zone grid cells are indirectly affected by the demand for biomass and thereby the changes are much smaller. The region-wide average rate of increase in corn production is 0.07%, whereas the region-wide average increasing in leaching is 4.6%. This contrasts sharply with percentage changes at the level of individual grid-cells.

electricity and biomass markets would have led to an overestimation of the demand for biomass in the neighborhood of these power plants. Furthermore, the impacts of additional total corn production, and additional nitrogen fertilizer use, on prices results in a reduction in corn production outside of the regions supplying biomass for cofiring power plants. These are impacts that would be missed altogether if we had undertaken the analysis solely at the level of individual power plants or watersheds, or restricted to only one domain such as the power system or agricultural markets

A separate strand of literature exploring the energy—water—land nexus takes a more aggregate view of the problem, restricting themselves to a coarser regional resolution in favor of offering national or even global coverage.[53] Here, the risk is that the analysis will not be sufficiently refined to capture different local processes. If, for example, we had modeled the entire MISO region as a single electricity generating unit, we would have also missed the fact that some power plants will cease generation under the cofiring mandate policy. More serious is the fact that, by treating the entire region as one unit of analysis, we would have registered only a modest increase in nitrate leaching (just 5% across the upper MISO region). This would have obscured the extremely large increases in leaching in particular regions. For example, in southern Illinois, in close proximity to the power plants along the Mississippi River, the increase in nitrate leaching reaches 60% over baseline. Furthermore, leaching is already a significant problem in Illinois.[51] Averaging these effects over the entire region obscures a potential serious environmental issue.

By combining a suite of energy, resource use, and agricultural models, this paper has demonstrated that it is possible to combine fine-scale analysis of nexus issues within a larger, market-based context, thereby capturing local heterogeneities while also integrating dynamic feedbacks from local to regional, national, and global levels.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b07458.

Further details are provided regarding linkages between the dynamically applied models and associated objectives (Figure 1); supply functions, including parameters used to calculate quantities and costs of corn residue (Table S1), supply functions of corn residue for three randomly selected plants (Figure S1), and estimates of the supply function for each power plant (Table S2); biomass demand; Unit Commitment model, including nomenclature, objective, operating constraints, representation of biomass cofiring technology mandate in the UC model, implementation of the UC model, results, and number of coal plants in MISO with capacity factors below 40% and above 60% (out of 72 total) (Table S3); equilibrating supply of biomass with demand to identify supply zones; iterative process to find the equilibrium power variables (Figure S2); supply zones of corn residues around power plants representing conditions when one power plant cofires at a time (Figure S3); Agro-IBIS simulation methodology; SIMPLE-G-US-CS model, including model structure, model validation, observed and simulated percentage change in validated variables (Table S4), experimental design, and experiment shocks applied to model baseline at the grid-cell level (Figure S6) (PDF)

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Notes

The authors declare no competing financial interest.

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