Designing Payments for Multiple Ecosystem Services with Advanced Biofuels in the Mississippi River Basin

Xinxin Fan[1] (xinfan@illinois.edu),
Madhu Khanna[1,2] (khanna1@illinois.edu),
Theodore Hartman[3] (theodore@iastate.edu),
Andy Vanloocke[3] (andyvanl@iastate.edu)
[1] DOE Center for Advanced Bioenergy and Bioproducts Innovation, [2] Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, US.
[3] Department of Agronomy, Iowa State University, Ames, IA 50011, US.

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1. Introduction

Biofuels are being increasingly promoted as a low-carbon alternative to reduce the dependence on fossil fuels and mitigate greenhouse gas (GHG) emissions. Currently, the renewable fuels for transportation are dominated by conventional biofuels produced primarily from corn in the US, however, concerns about the competition between food and fuel production for cropland and its possible impacts on food prices are motivating a shift to advanced biofuels. Advanced biofuels can be produced from a variety of feedstocks, including annual and perennial energy crops and crop residues, that differ in their carbon (C) intensity and effects on soil organic carbon (SOC) stocks depending on their location of production in the rainfed region of the US. Dwivedi et al. (2015) estimated that compared to gasoline, savings in GHG emissions for ethanol derived from miscanthus was up to 156%, while that for corn stover (57% to 95%) was marginally below the threshold of at least 60% for cellulosic biofuels required by the Renewable Fuel Standard (RFS2). Likewise, it is expected that converting cropland to switchgrass or miscanthus can sequestrate more carbon in soil (Anderson-Teixeira et al., 2009; Qin et al., 2016), in contrast to harvesting crop residue for biofuels that could decrease SOC and increase carbon emissions from soil (Liska et al., 2014; Ruis and Blanco-Canqui, 2017).

The increase of corn-based ethanol production has been shown to worsen nitrogen (N) leaching through the Mississippi Atchafalaya River Basin (MARB) and contribute to hypoxia in the Gulf of Mexico (Alexander et al., 2008; David et al., 2010; Turner et. al., 2012; Ha et al., 2018; EPA, 2018). Perennial energy crops are promising feedstocks to produce biofuels as they can better utilize N and reduce N leakage relative to row crops, due to their extensive rooting systems and less fertilizer and tillage requirement (Vadas et al., 2008; Costello et al., 2009; Voigt et al., 2012; Smith et al., 2013; Hudiburg et al., 2016; Jin et al., 2019). However, the extent to which they can reduce N leakage will depend on whether they are grown on cropland and displace N-intensive corn production or on low opportunity cost marginal land. VanLoocke et al. (2017) found that if 40% of the land currently under corn were replaced by switchgrass or miscanthus in the MARB, the dissolved inorganic nitrogen (DIN) reaching the Gulf of Mexico would be declined by 15% and 20%, respectively. However, this land use change is exogenously predetermined, and its feasibility affected by various environmental, economic and social factors (e.g., soil condition, land management, and water availability) (Dale et al., 2010; Housh et al., 2015a) remains to be assessed. Although some advanced biofuel feedstocks such as energy crops can lead to negative carbon intensity biofuels and reduce N leakage, others like crop residues that are relative less costly to produce can lower soil carbon levels and worsen nutrient losses (Battaglia et al., 2021; Cibin et al., 2016).

The current biofuel policy has taken the form of volumetric mandates such as the RFS2 that distinguishes between different types of biofuels based on their feedstock type and carbon intensity level relative to policy determined threshold levels. The RFS2 does not create incentives for cellulosic biofuels that can lower carbon intensity below the threshold level or consider the water quality effects of the feedstocks used. It has been showed that RFS2 can worsen the Gulf Hypoxia while having GHG benefits that are lower than its potential (Lark et al., 2022; Gramig et al., 2013). As indicated by Ferin et al. (2021), the additional 16-billion-gallon cellulosic biofuel mandate of RFS2 will drive the production of least cost feedstocks (such as corn stover) rather than environmentally friendly perennial crops, and lead to an increase in N losses. Therefore, performance-based policies that reward biofuels based on their multi-dimensional ecosystem co-benefits are needed to supplement the biofuel mandate to achieve desired environmental outcomes. However, most extant studies have targeted on imposing policies in addition to a biofuel mandate to achieve a single environmental objective, such as a low carbon fuel standard and/or a carbon price policy to reduce GHG emissions (Chen et al., 2012; Huang et al., 2013), and a nitrate reduction policy to improve water quality (Housh et al., 2015a). Housh et al. (2015b) explored the implications of stacking GHG reduction and/or nitrate runoff reduction policies on a biofuel mandate but within a watershed. To the best of our knowledge, we are not aware of any study that considers multiple environmental benefits co-generated by advanced biofuels for policy design at the MARB scale.

Note that designing the performance-based policies can be challenging with correlated co-benefits and potential trade-offs among economic effects and environmental benefits. It necessitates an integrated assessment model that takes a holistic approach to determine the optimal combination of feedstocks, production locations and land types for maximizing net societal benefits while also achieving biofuel targets. Hence, we undertake this study by coupling an economic model (Biofuel and Environmental Policy Analysis Model (BEPAM)) (Chen et al., 2014; Chen et al., 2021) with an agroecosystem model Agro-IBIS (Integrated BIosphere Simulator−Agricultural Version) (VanLoocke et al., 2017), a nutrient transport and hydrologic model (Terrestrial Hydrologic Model with Biogeochemistry THMB (VanLoocke et al., 2017), and a biogeochemical model DayCent (Daily CENTURY) (Del Grosso et al., 2011) to simulate the economic and environmental impacts of achieving GHG and water quality targets individually and jointly in addition to a biofuel mandate similar to the RFS2 mandate over the 2025-2035 period (see Section 2), focusing on the MARB where nearly 90% of the U.S. corn and soybean production occurs (White et al., 2014; NASS, 2022), contributing to 70% of the nitrogen (N) delivered into the Gulf (Robertson and Saad, 2021). Our objectives are to (1) estimate the effects of meeting various levels of environmental reduction targets on land use, optimal feedstock mix and their spatial pattern of production, food and fuel prices, and fuel consumption; (2) examine the cost-effectiveness of the combinations of carbon tax and/or nitrate tax to achieve various policy targets, and the distribution of costs and benefits among food and fuel consumers and producers.

2. Methodology

2.1 Modeling Framework

We develop an integrated modeling approach to assess the impacts of supplementing a biofuel mandate associated with the RFS2 with two performance-based policies, nitrate leaching reduction and/or GHG emissions reduction on land use, mix of feedstock production and spatial distribution, food and fuel price, and fuel consumption; quantify the amount of GHG emissions and nitrate runoff, social welfare changes, and nitrate tax and/or carbon tax needed to achieve various environmental targets (Figure 1). In this modeling framework, we apply the Agro-IBIS model and the THMB model to simulate soil nitrate leaching rates of three different feedstocks for cellulosic biofuels that include two energy crops (miscanthus, switchgrass) and corn stover, and two food crops, corn and soybeans with different tillage and rotation choices, and delivery coefficients of nitrate leaching at the outlet of MARB to the Gulf, based on the same assumption about N application rates as BEPAM (Chen et al., 2021; Hudiburg et al., 2016); and DayCent model to simulate their soil carbon changes. In the absence of long term observed yields for miscanthus and limited data for switchgrass, we apply the Agro-IBIS model to simulate the potential yields of miscanthus and switchgrass following the modified algorithm developed by VanLoocke et al. (2012). These data simulated from three biophysical models are connected to drive simulations in BEPAM over the 2016-2035 period. We calculate the life-cycle GHG emissions from the transportation and agricultural sectors in the US. using methods and assumptions based on Chen et al. (2021), and measure nitrate losses to the Gulf at the outlet of the MARB (e.g., Donner and Kucharik, 2008; VanLoocke et al., 2017).

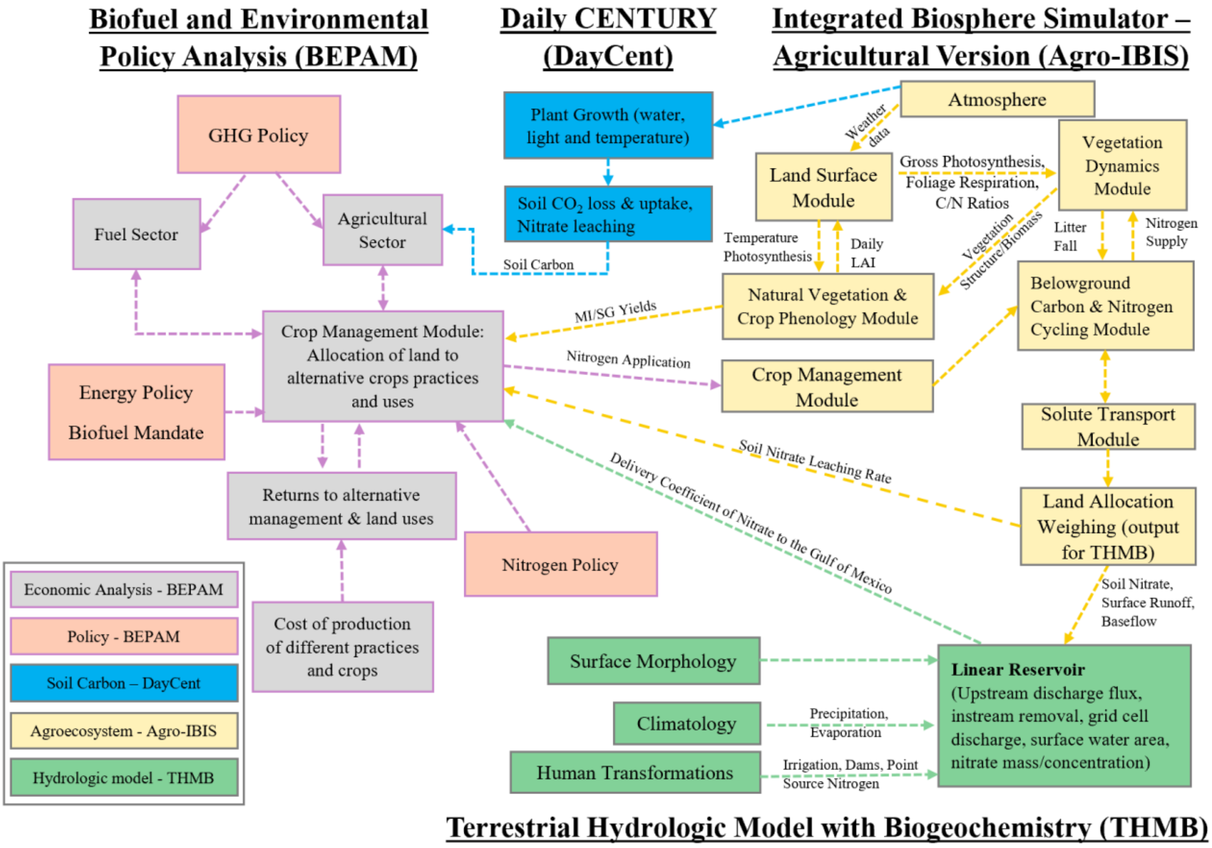

Figure 1. The integration modeling framework with the economic model BEPAM (gray and orange boxes) and the biophysical models DayCent (blue boxes), Agro-IBIS (yellow boxes), and THMB (green boxes).

2.2 Policy Scenarios

To analyze the economic and environmental effects that can be attributed to achieving two environmental outcomes, nitrate leaching reduction and GHG emission reduction in addition to a biofuel mandate motivated by the volumetric mandates of the RFS2, we simulated the following alternative policy scenarios:

(a) No-Policy: corn ethanol and biodiesel production are assumed to remain at their 2007 levels (annual production of 6.5 billion gallons and 0.3 billion gallons, respectively) over the 2016-2035 period.

(b) Corn Ethanol Mandate (baseline): annual corn ethanol production is capped at 15 billion gallons and annual biodiesel production is assumed to be at the level projected in the Annual Energy Outlook (AEO) by the U.S. Energy Information Administration (EIA) (EIA 2022) over the 2016-2035 period.

(c) Corn & Cellulosic Ethanol Mandate: cellulosic ethanol production is assumed to grow linearly from 0.23 billion gallon in 2016 to 16 billion gallon in 2035 while annual corn ethanol and biodiesel production are at the same levels as in the Corn Ethanol Mandate scenario.

(d) Nitrate Policy + Ethanol Mandate: a 10% nitrate reduction target based on the amount of nitrate leaching under the Corn Ethanol Mandate scenario, which is linearly increased over 2025-2035, is imposed in addition to the Corn Ethanol Mandate scenario (abbreviated as Corn Ethanol + NR10) or Corn & Cellulosic Ethanol Mandate scenario (abbreviated as Corn & Cellulosic Ethanol + NR10).

(e) GHG Policy + Ethanol Mandate: a 10% GHG emissions reduction target based on the amount of GHG emissions under the Corn Ethanol Mandate scenario, which is linearly increased over 2025-2035, is imposed in addition to the Corn Ethanol Mandate scenario (abbreviated as Corn Ethanol + GHGR10) or Corn & Cellulosic Ethanol Mandate scenario (abbreviated as Corn & Cellulosic Ethanol + GHGR10).

(f) Combined Policy + Ethanol Mandate: combined GHG Policy and Nitrate Policy, in which a 10% reduction in nitrate runoff and a 10% reduction GHG emissions based on the amounts of nitrate leaching and GHG emissions under the Corn Ethanol Mandate scenario that are linearly increased over 2025-2035, is supplemented to the Corn Ethanol Mandate (Corn Ethanol + NR10 & GHGR10) or Corn & Cellulosic Ethanol Mandate scenario (abbreviated as Corn & Cellulosic Ethanol + NR10 & GHGR10).

We enforce the mandates in BEPAM by creating annual blend rates to meet the volumetric targets of biofuels and biodiesel; these blend rates increase beyond 11.4% in 2016 to 25.3% by 2035 under the Corn & Cellulosic Ethanol Mandate scenario. By comparing outcomes from Corn Ethanol Mandate and Corn & Cellulosic Ethanol Mandate scenarios to those from the No-Policy scenario, we analyse the economic and environmental implications of biofuel mandates; then by comparing results under the Nitrate Policy + Ethanol Mandate, GHG Policy + Ethanol Mandate, and Combined Policy + Ethanol Mandate scenarios to that under the Corn Ethanol Mandate scenario, we isolate the effects of meeting multiple environmental objectives with and without cellulosic ethanol mandate from that of the corn ethanol mandate.

2.3 BEPAM

BEPAM is a multi-period, open-economy, price-endogenous, multi-market partial equilibrium model that integrates the agricultural and transportation sectors of the US economy and the trade in agricultural commodities, oil and petroleum products with the rest of the world. The model endogenously determines the optimal land use, production, and consumption decisions that maximize the sum of consumers' and producers' net benefits in multiple markets subject to various materials balances, land and resource availability, and policy constraints (Hudiburg et al., 2016; Chen et al., 2014; Chen et al., 2021). The model determines the welfare-maximizing mix of feedstocks and land allocation for alternative crops to achieve biofuel blending mandates and its implications on GHG emissions, nitrate runoff, and the welfare costs.

In the agricultural sector we assume given demand curves for food/feed crop domestically and from the rest of the world, since the US is a large exporter of agricultural commodities. The model considers spatial heterogeneity in crop and livestock production, where costs of production, yields, and land availability differ across crop reporting districts (CRDs) in the US. The optimal land allocation for twelve major row crops, three potential energy crops (miscanthus, switchgrass) and crop residues (corn stover and wheat straw) on cropland and marginal land is endogenously determined by maximizing social welfare subject to constraints on availability of land and historical mix of cropland use as well as the yields and agronomics of crop production over the period 2016-2035.

Mandate-induced demand for corn ethanol leads to increased demand for corn and a new equilibrium with higher corn price, expansion of corn production and acreage as well as a reduction in exports and domestic demand for food/feed. The expansion of corn acreage is likely to be met partly by diversion of land under alternative food crops and partly by the conversion of marginal land to crop production, which leads to nitrate losses and GHG emission releases. The cellulosic biofuel mandate creates incentives for harvesting crop residue and converting land to energy crop production. Production of energy crops is likely to commence on marginal land due to its low opportunity cost relative to cropland; constraints on the availability of marginal land can lead to the diversion of cropland to perennial energy crops and increases in row crop prices. The nitrate runoff and GHG emissions of cellulosic biofuels are likely to be lower than that of corn ethanol since cellulosic feedstocks particularly perennials, require less fertilizer inputs and land management, better utilize N and sequester carbon in soil, have higher yield of biofuel per unit of land, as well as receive co-product credits for electricity generated from converting biomass to fuel at a cellulosic biorefinery. Imposing nitrate leaching and/or GHG emissions reduction targets in addition to a biofuel mandate is expected to limit the expansion of corn production, motivate choosing less N and C intensive cultivation practices, such as shifting corn production from continuous corn to corn-soybean rotation, and aggravate converting cropland from row crops to perennials.

In the transportation sector we assume exogenously given downward sloping demand for Vehicle Kilometers Travelled (VKT) with alternative types of vehicles which leads to derived demands for gasoline, diesel and biofuel. The US is assumed as an importer in the oil market but a small, price-taking exporter in the world market for gasoline and diesel. Oil produced domestically and imported from the rest of the world is converted to gasoline and diesel at a fixed rate in the US (EIA, 2016). BEPAM specifies domestic oil supply functions and the oil demand and supply functions for the rest of the world.

The imposition of the biofuel blend mandate reduces domestic fossil fuel consumption and increases biofuel consumption by imposing an endogenously determined implicit tax on fossil fuels and an implicit subsidy on biofuels in the U.S (Chen et al., 2014). The reduction in domestic demand for gasoline and diesel by biofuels can reduce demand for imported oil which is refined in the US to produce petroleum products (and thereby affect the world price of oil) and it can also generate excess gasoline and diesel for export. The extent to which each of these occur are determined endogenously depending on the responsiveness of various supply and demand functions, the technological relationship between oil, gasoline and diesel, and the price of exports of petroleum products (see Chen et al., 2021). These fuel market effects have the potential to affect domestic and global fuel prices and oil consumption in the rest of the world and the US, with implications for GHG emissions. The effect of biofuel mandates on GHG emissions from the transportation and fuel sectors is ambiguous because although the direct displacement effect of low carbon biofuels replacing gasoline and diesel will reduce emissions, the fuel price effects of biofuel mandates could either strengthen or offset a part of the displacement effect. The overall effects of biofuel mandates on GHG emissions will depend on the magnitude of the displacement effect, the responsiveness of various fuel demand and supply curves in the model and the stringency of the biofuel mandate and are endogenously determined in BEPAM (as discussed in more detail in Chen et al., 2021). The addition of the GHG reduction target to a biofuel mandate is likely to be achieved by further reducing gasoline and diesel consumption and promoting cellulosic ethanol from more environmentally friendly feedstocks (e.g., miscanthus and switchgrass) than that of a biofuel mandate alone, as well as changing fuel prices. The extent of these effects, similar to implementing biofuel mandates alone, will also endogenously determined in BEPAM. The influences of supplementing the nitrate reduction policy to a biofuel mandate on the transportation sector largely depends on the extent to which the nitrate leaching reduction target will affect fuel crop production.

We determine the domestic social welfare as the discounted value of the sum of the consumer and producer surplus[1] in 2016 prices based on the equilibrium food and fuel prices and production levels in the agricultural and transportation sectors in each year 2016-2035 with and without the biofuel mandates and/or environmental policies, assuming a 3% discount rate[2]. By comparing to the No-Policy or Corn Ethanol Policy scenario, we then estimate the loss in discounted social welfare under other alternative policy scenarios (see Section 2.2, scenario (c) to (f)) to determine the welfare costs of the biofuel mandates and/or environmental reduction targets. The model has been well validated by comparing simulated outcomes in the fuel and agricultural sectors for each of the years 2016-2019 with observed data for each of those years (Table S1 and S2 of the Supporting Information (SI)).

2.4 Agri-IBIS Model

The agroecosystem model Agro-IBIS, simulates energy, water, carbon, and nitrogen flux between the soil−plant−atmosphere continuum at an hourly time step by simulating biophysical cycles and biochemical processes (Figure 1) at 0.5° × 0.5° spatial resolution over 30 years under different weather conditions (Ferin et al. 2021; VanLoocke et al., 2017). This model includes C3 and C4 temperature-dependent photosynthetic pathways consisting of enzyme kinetic properties and leaf-level stomatal conductance and energy balances (Farquhar et al., 1980; Collatz et al., 1991) that are scaled up to the canopy level (Thompson et al., 1995a; 1995b). Carbon and N fluxes and pools are also calculated and account for the

[1] Consumer surplus is estimated for the two sectors as the area under national demand curves for each of the agricultural products and vehicle kilometers traveled for different types of vehicles. Producer surplus is estimated from national supply curves for gasoline and diesel. See the SI of Chen et al. (2021) for model details.
[2] EPA (2017) recommended three social discount rates: 2.5%, 3% and 5%. Here we use the medium value 3%. A more comprehensive discussion of the social discount rate can be found at Boardman et al. (2017).

exchange from uptake by plants and from the soil and atmosphere and are partitioned within different parts of the plants (roots, stems, leaves, etc.) (Kucharik et al., 2000). The land cover and crop management choices represented in the Agro-IBIS simulations consisted of continuous corn, continuous soybean, corn−soybean rotations, spring and winter wheat, natural vegetation, miscanthus, and switchgrass for all available land. Other assumptions and approach remain same as VanLoocke et al. (2017) except N application rates from BEPAM. We average soil nitrate leaching rates over 30 years and resolution grids in each CRD to drive BEPAM simulation.

2.5 THMB Model

The hydrological model THMB simulates transport, removal, and storage of N and water at multiple temporal resolutions for the 5 min × 5 min (∼7 km×9 km) spatial resolution. In this study, THMB uses heterogeneously weighted output data from Agro-IBIS simulations to estimate how much nitrate reach the outlet of a specific watershed. For this study, we use the MARB outlet where the Mississippi River meets the Gulf of Mexico, and average the delivery coefficients of nitrate to the Gulf over grids in each CRD to match the THMB output with the CRD resolution of BEPAM. For additional information, see VanLoocke et al. (2017).

2.6 DayCent Model

DayCent simulates exchanges of carbon, nutrients and trace gases among the atmosphere, soil and plants as a function of light, temperature and water and nutrient availability in response to changes in land use, management practices and climate (Campbell et al., 2014; Cheng et al. 2014; Hudiburg et al., 2015). The average soil carbon sequestration rates of row crops (corn and soybeans across rotation and tillage choices), perennials (miscanthus and switchgrass), and corn stover at the county scale over 30-year different weather conditions are simulated using DayCent, in which the weather input data are obtained from CRUNCEP (Viovy 2018) and DayMet (Thornton et al. 2020) databases. We then average the county-level output to obtain CRD-level rates of soil carbon for BEPAM analysis.

3. Results

3.1 Economic and environmental effects of the biofuel mandates alone

We find that the Corn Ethanol Mandate will result in a significant decrease in the economic net benefits over 2016-2035 relative to the No-Policy scenario (column 2 of Panel A, Table 1). In the transportation sector, the corn ethanol mandate will increase gasoline and diesel prices, lowering fuel consumer's benefits by $237 billion ((-) 2.5%). The agricultural producers' benefits will be $280 billion higher than that under No-Policy because of the increases in food crop prices and planted acreage induced by corn ethanol expansion, however, there is a loss in the agricultural consumers' benefits ($127 billion ((-) 4.7%)). Generally, implementing the Corn Ethanol Mandate will lead to a net economic decline of $ 98 billion ((-) 0.7%) relative to the No-Policy.

Under the Corn & Cellulosic Ethanol Mandate scenario, the overall loss in the net economic benefit is $159 billion ((-) 1.1%) compared to the No-Policy (column 3 of Panel A, Table 1), which is about 1.6 times higher than the net economic loss under the Corn Ethanol Mandate scenario. While the economic benefits in the agricultural sector will increase by $169 billion (4.3%), the benefits in the transportation sector will be reduced by $319 billion ((-) 3.4%) over 2016–2035 relative to the No-Policy scenario.

The amounts of nitrate export to the Gulf and GHG emissions in 2035 under No-Policy, Corn Ethanol Mandate, and Corn & Cellulosic Ethanol Mandate scenarios are shown in Panel B of Table 1. We find that compared to No-Policy scenario, the total nitrate leaching in 2035 under the Corn Ethanol Mandate scenario will increase by 15% in the MARB due to the expansion of corn production while there is a 4% reduction in GHG emissions caused by displacing fossil fuels by lower carbon intensity ethanol. The implementation of an additional cellulosic mandate will lead to a smaller increase in nitrate leaching while more savings in GHG emissions than that under Corn Ethanol Mandate; the percentage changes in nitrate leaching and GHG emissions relative to the No-Policy scenario are now 12.9%, and (-)10.6%, respectively, which will be achieved by growing energy crops that have low nitrogen requirement and high soil carbon sequestration to displace row crops, as well as replacing fossil fuel with low carbon biofuels.

Table 1. Economic and environmental effects of biofuel mandates alone

Scenario	No-Policy (1)	Corn Ethanol Mandate (2)	Corn & Cellulosic Ethanol Mandate (3)
Panel A: Social welfare over 2016 – 2035 ($ billion)*			
	Quantity	Absolute change (% change) relative to No-Policy	
Transportation sector	9394	-238 (-2.5%)	-319 (-3.4%)
Crude oil producers	80	-1 (-1.4%)	-1 (-1.4%)
Gasoline consumers	5427	-158 (-2.9%)	-211 (-3.9%)
Diesel consumers	3887	-79 (-2.0%)	-107 (-2.8%)
Agricultural sector	3888	153 (3.9%)	169 (4.3%)
Agricultural consumers	2700	-127 (-4.7%)	-129 (-4.8%)
Agricultural producers	1188	280 (23.6%)	298 (25.1%)
Government revenue	1060	-13 (-1.2%)	-9 (-0.9%)
Total welfare	14341	-98 (-0.7%)	-159 (-1.1%)
Panel B: Nitrate leaching and GHG emissions, 2035			
	Quantity	% change relative to No-Policy	
Nitrate leaching (million MT)	0.8	15.1%	12.9%
GHG emissions (billion MT)	2.0	-4.3%	-10.6%

Note: * all values are discounted cumulative numbers over 2016-2035 (discounted rate 3%).

3.2 Effects of alternative policies on the agricultural sector

Under the Corn Ethanol Mandate, the demand for corn production will increase by 17% in 2035, which will increase land under corn production by 18% compared to No-Policy; this increase is achieved mainly by increasing land under continuous corn (15.4%) and that under corn–soybean rotation (20.3%), relative to the No-Policy scenario (Table S3 of the SI). Additionally, land under wheat and soybean also increases by 4.5% and 2.9%, respectively.

Such increases in land to grow N intensive row crop coincide with the increase in nitrate leaching relative to No-Policy (Table 1), which has been shown to have deleterious effects on water quality (Alshawaf et al., 2016; Jaynes et al., 2001).

Table 2 (column 2) shows the results of a 10% nitrate leaching reduction target is imposed in addition to the Corn Ethanol Mandate. We find that land under corn declines by 0.9 million ha (3.1%) in the MARB while there is a 0.4 million ha increase (5.6%) in corn acreage outside the MARB, relative to the Corn Ethanol Mandate scenario; land under soybean increases in the MARB due to the increase in land under corn-soybean rotation. The addition of the nitrate reduction target to the Corn Ethanol Mandate also leads to land conversion from continuous corn to corn-soybean rotation in the MARB; also, there is a significant reduction ((-) 33.3%) in land under conventional tillage for continuous corn, and for corn-soybean rotation, the decline in land under conventional tillage is only 2.1% while land under no-till increases by 17.8%, relative to the Corn Ethanol Mandate scenario. The spatial changes in land under continuous corn and corn-soybean rotation under Corn Ethanol + NR10 are shown in Figure S1 (a1) and S1 (a2) with land under continuous corn replacing corn-soybean largely occurring in Indiana and Nebraska. When imposing a 10% reduction in GHG emissions in addition to the Corn Ethanol Mandate, land under crop production (except soybeans) generally decreases to reduce GHG emissions, relative to Corn Ethanol Mandate (column 3 of Panel A, Table 2). The results also show land under conventional tillage for both continuous corn and corn-soybean rotation in the MARB declines dramatically ((-) 60.2% and (-) 99.0%, respectively); in contrast, land acreage of corn-soybean rotation under no-till is more than two times as large as that under the Corn Ethanol Mandate alone. Similarly, the addition of a 10% reduction in both nitrate leaching and GHG emissions to the Corn Ethanol Mandate will lead to slightly more decreases in crop production than that of supplementing the Corn Ethanol Mandate with the nitrate runoff or GHG emission reduction target alone in the MARB, despite there is a small increase in land under soybeans for three environmental reduction scenarios induced by the expansion of land under corn-soybean rotation. The spatial changes in land under continuous corn and corn-soybean rotation under the Corn Ethanol + GHGR10 (Figure S1 (b1) and S1 (b2)) and Corn Ethanol + NR10&GHGR10 (Figure S1 (c1) and S1 (c2)) show similar patterns to that under Corn Ethanol + NR10.

We estimate that under the Corn Ethanol Mandate, higher corn demand will increase its price by 26.9%, and the price of soybeans increases by 15.3% as the production of biodiesel increases the demand for soybeans, relative to the No-Policy scenario; while the price of wheat decreases by 5.7% because of the slight increases (4.5%) in land under wheat and its yield per unit land increases (Table S3 of the SI). Relative to the Corn Ethanol Mandate, the addition of nitrate runoff and/or GHG emissions reduction target to the Corn Ethanol Mandate will result in even higher prices for corn and wheat because of the decreases in land under these crops; on the contrary, a lower price of soybeans as soybeans production will increases by more productive land released from corn being used to grow soybeans, especially in the MARB, and its yield per unit land increasing (column 2-4 of Panel C, Table 2).

Relative to the Corn Ethanol Mandate, the implementation of Corn & Cellulosic Ethanol Mandate will lead to an additional expansion of land for crop production by 2 M ha in 2035, while the land under row crops will decrease slightly by 2 M ha (column 2 of the Table 3). The prices of corn, soybeans, and wheat will further increase by 0.6%, 1.8%, and 4.9% in 2035, respectively as the additional 16 billion gallons of cellulosic ethanol mandate will lead to less land under each of these crops than that of the Corn Ethanol Mandate scenario. Total land under corn production remains similar to that under the Corn Ethanol Mandate, due to incentives for harvesting corn stover as cellulosic feedstock. The addition of the nitrate leaching and/or GHG emissions reduction to the Corn & Cellulosic Ethanol Mandate will further decrease land under corn and wheat and then lead to higher prices than that under the Corn & Cellulosic Ethanol Mandate scenario. The changes in land under continuous corn and corn-soybean rotation for scenarios of imposing two environmental reduction targets individually and jointly in addition to the Corn & Cellulosic Ethanol Mandate across the US. are depicted in Figure S2. These spatial patterns of land use changes by rotation are similar to that of imposing these environmental targets in addition to the Corn Ethanol Mandate but more regions will experience reduction in land under continuous corn within the MARB, such as CRDs in Nebraska, Kansas, Oklahoma, Tennessee, Mississippi, Alabama, and Carolinas. We also find that supplementing the Corn Ethanol Mandate or Corn & Cellulosic Ethanol Mandate with the nitrate leaching reduction target alone will lead to more decreases in land under continuous corn and more increases in land under corn-soybean rotation than that with the GHG emissions reduction target alone in the MARB; while the addition of the GHG Policy to a biofuel mandate will reduce more land under conventional tillage for continuous corn and convert almost all the land under conventional tillage to no-till for corn-soybean rotation.

Under the Corn & Cellulosic Ethanol Mandate scenario, 4.2 M ha land will be converted to energy crops in 2035 with two third occurring in the MARB. Relative to the Corn & Cellulosic Ethanol Mandate scenario, the addition of a 10% nitrate leaching reduction to the Corn & Cellulosic Ethanol Mandate will increase the land acreage of energy crops by 0.2 million ha in the MARB; but the increase in landunder energy crops is much higher (1 million ha) under the Corn & Cellulosic Ethanol Mandate + GHGR10 due to the higher soil carbon sequestration by the increase in energy crop production. Figure S3 shows the spatial changes in land under miscanthus in the US. across different scenarios related to the Corn & Cellulosic Ethanol Mandate. We find that there are little differences in the spatial distribution of land under miscanthus between the scenarios of the Corn & Cellulosic Ethanol Mandate with and without a 10% Nitrate Policy; while the addition of a 10% GHG Policy will lead to land under miscanthus moving north in the MARB, such as producing miscanthus in Pennsylvania and Dakotas.

Table 2. Effects of imposing nitrate leaching and/or GHG emissions reduction targets in addition to the Corn Ethanol Mandate on the agricultural sector in 2035.

Scenario	Corn Ethanol Mandate (baseline) (1)	Corn Ethanol + NR10 (2)	Corn Ethanol + GHGR10 (3)	Corn Ethanol + NR10 & GHGR10 (4)
Panel A: Land allocation by crop (million ha)				
	Quantity	% change relative to Corn Ethanol Mandate (baseline)		
Total land under crop production	113.7	-1.0%	-1.1%	-1.4%
Corn (MARB)	28.4	-3.1%	-2.7%	-3.6%
Corn (non-MARB)	6.4	5.6%	-2.7%	-1.9%
Soybeans (MARB)	27.7	0.7%	1.5%	1.3%
Soybeans (non-MARB)	7.1	-4.5%	1.5%	1.6%
Wheat (MARB)	10.8	-1.8%	-4.2%	-4.9%
Wheat (non-MARB)	6.3	0.1%	-1.1%	-1.1%
Other crops (MARB)	13.7	-1.8%	-1.3%	-1.7%
Other crops (non-MARB)	13.2	-0.1%	-0.5%	-0.2%
Panel B: Land allocation by rotation (million ha)				
	Quantity	% change relative to Corn Ethanol Mandate (baseline)		
Continuous corn (MARB)	13.2	-15.2%	-8.7%	-18.3%
Conventional tillage	0.9	-33.3%	-60.2%	-63.7%
No-till	12.3	-13.8%	-4.9%	-14.9%
Continuous corn (non-MARB)	3.5	6.5%	-3.2%	-2.7%
Conventional tillage	0.0	--	--	--
No-till	3.5	6.5%	-3.2%	-2.7%
Corn-Soybean rotation (MARB)	30.3	7.4%	2.5%	9.1%
Conventional tillage	15.8	-2.1%	-99.0%	-98.8%
No-till	14.5	17.8%	113.5%	127.2%
Corn-Soybean rotation (non-MARB)	5.9	4.4%	-2.0%	-1.0%
Conventional tillage	2.0	17.2%	-100.0%	-100.0%
No-till	3.9	-2.2%	48.3%	49.8%
Panel C: Row Crop Price ($/MT)				
	Price	% change relative toCorn Ethanol Mandate (baseline)		
Corn	138.4	5.0%	4.5%	5.0%
Soybeans	322.8	-0.9%	-4.6%	-4.6%
Wheat	180.5	1.5%	4.8%	6.4%

Note: NR10 refers to 10% Nitrate leaching Reduction; GHGR10 refers to 10% GHG emissions Reduction.

Table 3. Effects of imposing nitrate leaching and/or GHG emissions reduction targets in addition to the Corn & Cellulosic Ethanol Mandate on the agricultural sector in 2035.

Scenario	Corn Ethanol Mandate (baseline) (1)	Corn & Cellulosic Ethanol Mandate (2)	Corn & Cellulosic Ethanol + NR10 (3)	Corn & Cellulosic Ethanol + GHGR10 (4)	Corn & Cellulosic Ethanol + NR10 & GHGR10 (5)
Panel A: Land allocation by crop (million ha)					
Row crops (a)	Quantity	% change relative to Corn Ethanol Mandate (baseline)			
Corn (MARB)	28.4	-2.4%	-4.4%	-3.5%	-4.7%
Corn (non-MARB)	6.4	-1.7%	0.1%	-2.6%	-1.6%
Soybeans (MARB)	27.7	-0.6%	-0.9%	-0.5%	-0.8%
Soybeans (non-MARB)	7.1	-4.1%	-4.4%	-3.0%	-3.7%
Wheat (MARB)	10.8	-4.3%	-5.4%	-6.4%	-7.8%
Wheat (non-MARB)	6.3	-0.3%	0.0%	-1.8%	-1.6%
Other crops (MARB)	13.7	-3.2%	-4.3%	-6.4%	-7.1%
Other crops (non-MARB)	13.2	0.2%	0.1%	-1.8%	-1.5%
Energy crop (b)		Absolute value (million ha)			
Miscanthus (MARB)	--	2.7	2.9	3.7	3.8
Miscanthus (non-MARB)	--	1.5	1.6	1.9	1.8
Total land under crop production (a+b)	113.7	1.9%	1.4%	1.9%	1.4%
Panel B: Land allocation by rotation (million ha)					
	Quantity	% change relative to Corn Ethanol Mandate (baseline)			
Continuous corn (MARB)	13.2	-4.1%	-17.5%	-8.4%	-19.2%
Conventional tillage	0.9	2.9%	-21.6%	-22.5%	-46.0%
No-till	12.3	-4.7%	-17.2%	-7.4%	-17.3%
Continuous corn (non-MARB)	3.5	-3.0%	-2.7%	-3.4%	-2.6%
Conventional tillage	0.0	--	--	--	--
No-till	3.5	-3.0%	-2.7%	-3.4%	-2.6%
Corn-Soybean rotation (MARB)	30.3	-1.0%	7.0%	0.8%	7.9%
Conventional tillage	15.8	-30.7%	-40.3%	-99.5%	-98.5%
No-till	14.5	31.6%	58.7%	110.5%	124.3%
Corn-Soybean rotation (non-MARB)	5.9	-1.5%	2.1%	-1.8%	-0.5%
Conventional tillage	2.0	-27.4%	-19.7%	-100.0%	-100.0%
No-till	3.9	11.8%	13.3%	48.5%	50.5%
Panel C: Row Crop Price ($/MT)					
	Price	% change relative to Corn Ethanol Mandate (baseline)			
Corn	138.4	0.6%	3.9%	4.5%	6.2%
Soybeans	322.8	1.8%	2.3%	0.5%	0.9%
Wheat	180.5	4.9%	4.9%	8.0%	8.8%

Note: NR10 refers to 10% Nitrate leaching Reduction; GHGR10 refers to 10% GHG emissions Reduction.

3.3 Effects of alternative policies on the transportation sector

The implementation of the Corn Ethanol blending Mandate (and biodiesel mandate) will increase biofuel consumption by implicitly subsidizing biofuels and taxing the fossil fuels, which create wedges between their consumer and producer prices (Chen et al., 2014, Holland et al., 2015). We find the Corn Ethanol Mandate will raise the consumer prices ($/gallon) of diesel by 4.2% and gasoline by 4.7%; and the price of diesel vehicle kilometers traveled (VKT) ($/km) by 4.2% and the price of gasoline VKT by 4.6%; which will decrease diesel consumption by 2.8% and gasoline consumption by 7.5%; and their VKT by 0.8% and 1.6%, respectively in 2035, relative to the No-Policy scenario (Table S4 of the SI). The reduction in gasoline consumption will be 6.3% larger than the increase in biofuel consumption on a gasoline energy-equivalent basis, indicating a negative domestic rebound effect (a gallon of biofuel will displace more than an energy equivalent gallon of gasoline in the US.).

The implicit tax imposed by the 16-billion-gallons cellulosic ethanol mandate will increase the consumer prices of gasoline and diesel by around 10%, and lead to a high reduction in diesel and gasoline consumption by 2.2 billion gallons ((-) 4%) and 19.4 billion gallons ((-) 19%), respectively, relative to the No-Policy. The prices of diesel and gasoline VKT ($/km) are 10.4% and 8.8% higher, respectively, than that under No-Policy, with a 2.0% decrease in diesel VKT and a 3.1% reduction in gasoline VKT (Table S4 of the SI). We find the domestic rebound effect will be more negative under the cellulosic mandate due to the higher cost of cellulosic biofuels, and the reduction in gasoline will be 12.8% larger than the energy-equivalent increase in biofuel.

Table 4 and Table 5 shows the fuel consumption and prices in 2035 simulated from supplementing the Corn Ethanol Mandate or Corn & Cellulosic Ethanol Mandate with a 10% reduction target in nitrate leaching and/or GHG emissions based on the amounts of leaching and emissions under the Corn Ethanol Mandate. Relative to the Corn Ethanol Mandate scenario, the addition of a 10% nitrate leaching reduction to a biofuel mandate rarely induces any changes in the transportation sector, while the addition of a 10% reduction in GHG emissions to the Corn Ethanol Mandate or Corn & Cellulosic Ethanol Mandate will significantly raise the prices of high GHG-intensity fossil fuels and reduce their consumption. Specifically, under the Corn Ethanol + GHGR10 scenario, the consumer price of diesel ($/gallon) will increase by 34.0% and that of gasoline by 24.9% relative to that under the Corn Ethanol Mandate, with a 7.2% and 9.7% decline in diesel and gasoline consumption, respectively. The increases in the prices of diesel and gasoline VKT ($/km) are similar to that of their consumer prices, which will reduce the diesel VKT by 6.9% and gasoline VKT by 9.2%. The implementation of the Corn & Cellulosic Ethanol + GHGR10 scenario will lead to lower increases in fuel prices and smaller decreases in their consumption than that under Corn Ethanol + GHGR10, as GHG savings from replacing gasoline with miscanthus-based ethanol will largely offset the GHG emissions from consuming gasoline and diesel. The addition of a 10% reduction in both nitrate leaching and GHG emissions to a biofuel mandate exerts almost equivalent effects on the transportation sector to that of supplementing a biofuel mandate with a 10% GHG reduction target alone because the 10% nitrate reduction target imposed in addition to a biofuel mandate will be largely achieved by changing land use of row crops, such as reducing land under N intensive row crops, converting land from continuous corn to corn-soybean rotation, and motivating land cultivation with no-till practice rather than conventional tillage.

Table 4. Effects of imposing nitrate leaching and/or GHG emissions reduction targets in addition to the Corn Ethanol Mandate on the transportation sector in 2035.

Scenario	Corn Ethanol Mandate (baseline) (1)	Corn Ethanol + NR10 (2)	Corn Ethanol + GHGR10 (3)	Corn Ethanol + NR10 & GHGR10 (4)
Panel A: Fuel Consumption (billion gallons)				
	Quantity	% change relative to Corn Ethanol Mandate (baseline)		
Diesel	53.3	0.0%	-7.2%	-7.1%
Gasoline	94.2	0.0%	-9.7%	-9.6%
Corn Ethanol	14.6	-0.1%	-6.3%	-6.4%
Panel B: Consumer fuel prices (US) ($/gallon)				
	Price	% change relative to Corn Ethanol Mandate (baseline)		
Diesel	2.2	0.0%	34.0%	33.8%
Gasoline	2.5	0.0%	24.9%	24.8%
Corn ethanol	2.8	1.8%	1.7%	1.9%
Panel C: Vehicel kilometers traveled (billion km)				
	Quantity	% change relative to Corn Ethanol Mandate (baseline)		
Diesel	893.2	0.0%	-6.9%	-6.9%
Gasoline	4713.1	0.0%	-9.2%	-9.1%
Panel D: Price of vehicel kilometers traveled ($/km)				
	Quantity	% change relative to Corn Ethanol Mandate (baseline)		
Diesel	0.139	0.0%	34.0%	33.8%
Gasoline	0.056	0.0%	24.9%	24.8%

Note: NR10 refers to 10% Nitrate leaching Reduction; GHGR10 refers to 10% GHG emissions Reduction.

Table 5. Effects of imposing nitrate leaching and/or GHG emissions reduction targets in addition to the Corn & Cellulosic Ethanol Mandate on the transportation sector in 2035.

Scenario	Corn Ethanol Mandate (baseline) (1)	Corn & Cellulosic Ethanol Mandate (2)	Corn & Cellulosic Ethanol + NR10 (3)	Corn & Cellulosic Ethanol + GHGR10 (4)	Corn & Cellulosic Ethanol + NR10 & GHGR10 (5)
Panel A: Fuel Consumption (billion gallons)					
	Quantity	% change relative to Corn Ethanol Mandate (baseline)			
Diesel	53.3	-1.3%	-1.3%	-3.5%	-3.4%
Gasoline	94.2	-12.4%	-12.4%	-14.3%	-14.2%
Corn Ethanol	14.6	-6.2%	-6.2%	-6.3%	-6.4%
		Quantity			
Cellulosic Ethanol		16.0	16.0	16.0	16.0
from corn stover		8.6	8.2	7.7	7.5
from miscanthus		7.1	7.6	8.2	8.3
Panel B: Consumer fuel prices (US) ($/gallon)					
	Price	% change relative to Corn Ethanol Mandate (baseline)			
Diesel	2.2	6.0%	6.0%	16.6%	15.9%
Gasoline	2.5	4.8%	4.8%	10.4%	10.0%
Corn ethanol	2.8	0.1%	1.3%	1.5%	2.3%
		Price			
Cellulosic ethanol		3.3	3.3	4.5	4.4
Panel C: Vehicle kilometers traveled (billion km)					
	Quantity	% change relative to Corn Ethanol Mandate (baseline)			
Diesel	893.2	-1.2%	-1.2%	-3.4%	-3.2%
Gasoline	4713.1	-1.6%	-1.6%	-3.2%	-3.1%
Panel D: Price of vehicle kilometers traveled ($/km)					
	Quantity	% change relative to Corn Ethanol Mandate (baseline)			
Diesel	0.1	6.0%	6.0%	16.6%	15.9%
Gasoline	0.1	4.0%	4.0%	7.8%	7.6%

Note: NR10 refers to 10% Nitrate leaching Reduction; GHGR10 refers to 10% GHG emissions Reduction.

3.4 Economic and environmental effects of alternative policies

Table 6 shows the effects of supplementing the Corn Ethanol Mandate with a 10% reduction in nitrate leaching and/or GHG emissions independently and jointly on net economic benefits among producers and consumers in transportation and agricultural sectors over 2016-2035 period, nitrate leaching and GHG emissions in 2035, and the nitrate and/or carbon taxes needed to achieve these environmental targets. Relative to the Corn Ethanol Mandate scenario, the addition of a 10% nitrate leaching reduction to the Corn Ethanol Mandate will minorly change net economic benefits by lowering the benefits of fuel consumers by $2 billion and that of agricultural consumers by $1 billion due to the increases in crop and fuel prices; while increasing agricultural producers' benefits by $4 billion (column 2 in Table 6). As a result, there is a $1 billion increase in net economic benefits under the Corn Ethanol + NR10. However, under the Corn Ethanol + GHGR10 scenario, there is significant decline in the economic net benefits over 2016–2035 (column 3 in Table 6) compared to the Corn Ethanol Mandate. In the transportation sector, the Corn Ethanol Mandate combined with the 10% GHG policy will highly increase the gasoline and diesel prices (see Table 4), and as a result, reduce fuel consumers' benefits by $ 332 billion ((-) 3.6%). The net economic benefits in the agricultural sector will change marginally, with a $1 billion increase in the agricultural consumers' benefit but a decrease of $5 billion in the agricultural producers' benefits due to a larger planted acreage (1.5%) of soybeans and its lower price ((-) 4.6%), relative to the Corn Ethanol Mandate scenario. Overall, the addition of a 10% reduction in GHG emission will lead to a net economic loss of $355 billion. Imposing a 10% Nitrate Policy and 10% GHG Policy jointly in addition to the Corn Ethanol Mandate will also raise the fuel prices and lower fuel consumers' benefits while slightly affect the net economic benefits in the agricultural sector, similarly to that of stacking a 10% GHG Policy alone on the Corn Ethanol Mandate.

The addition of the10% Nitrate Policy to the Corn Ethanol Mandate shows a co-benefit of reducing GHG emissions by 0.2% in 2035, which can be attributed to the declines in crop production and diversion of land management practice from conventional tillage to no-till. The nitrate tax needed to achieve this 10% Nitrate Policy is estimated to be $5.3/kg. Whereas, supplementing the Corn Ethanol Mandate with a 10% GHG emissions reduction will result in a much higher co-benefit (a 5.6% reduction in nitrate runoff), but the carbon tax is also high (\$67.7/MT CO_2e) with a net economic loss of \$355 billion, relative to the Corn Ethanol Mandate scenario. Compared to stacking a 10% GHG emissions reduction alone on the Corn Ethanol Mandate, the addition of a 10% reduction in both nitrate runoff and GHG emissions will be more cost-effective by achieving higher environmental targets with the carbon tax being 1.9% lower and net economic loss being $3 billion less. Moreover, under this Corn Ethanol + NR10 & GHGR10, the nitrate tax needed is 67.7% lower than that under the Corn Ethanol + NR10 Nitrate Policy, but the welfare cost will increase by $353 billion mainly because of the substantial welfare loss of reducing gasoline and diesel consumption to achieve GHG savings.

The implementations of Corn & Cellulosic Ethanol Mandate with and without a 10% nitrate leaching reduction target will lead to similar amounts of changes in net economic benefits among producers and consumers in the agricultural and transportation sectors relative to the Corn Ethanol Mandate scenario (Table 7). The net economic benefits will primarily decline for fuel consumers, while increase for agricultural producers; and the total economic loss will be 0.4% of the total economic benefits under the Corn Ethanol Mandate. The addition of a 10% Nitrate Policy to the Corn & Cellulosic Ethanol Mandate will lead to a further reduction ((-) 0.5%) in GHG emissions as a co-benefit, compared to the Corn & Cellulosic Ethanol Mandate, and the nitrate tax will be $3.8/kg to achieve a 10% reduction in nitrate runoff. The welfare changes under the Corn & Cellulosic Ethanol + NR10 & GHGR10 are similar to that under the Corn & Cellulosic Ethanol + GHG10, with a net economic loss of $99 billion and $102 billion, respectively, relative to the Corn Ethanol Mandate scenario. Imposing two environmental targets jointly in addition to the Corn & Cellulosic Ethanol Mandate can achieve a higher GHG emissions reduction by paying a lower nitrate tax than that of stacking a 10% Nitrate Policy alone on the biofuel mandates despite the Corn & Cellulosic Ethanol + NR10 & GHGR10 will lead to a higher welfare cost of $40 billion. Compared to the addition of a 10% GHG Policy alone to the Corn & Cellulosic Ethanol Mandate, supplementing the ethanol mandates with a 10% reduction in both nitrate leaching and GHG emissions will result in an additional 5.5% decrease in nitrate runoff, a smaller welfare cost by $3 billion lower, and the carbon tax needed is also 0.6% lower than that under the Corn & Cellulosic Ethanol + GHGR10 scenario. Moreover, applying a nitrate tax would be practically challenging since nitrate leaching is a non-point pollutant and is difficult to quantify and attribute to particular sources. The results show that a carbon tax also can be used to reduce nitrate runoff but at a higher welfare cost.

Table 6. Economic and environmental effects of imposing nitrate leaching and/or GHG emissions reduction targets in addition to the Corn Ethanol Mandate

Scenario	Corn Ethanol Mandate (baseline) (1)	Corn Ethanol + NR10 (2)	Corn Ethanol + GHGR10 (3)	Corn Ethanol + NR10 & GHGR10 (4)
Panel A: Social welfare over 2016 – 2035 ($ billion)				
	Quantity	Absolute change (% change) relative to Corn Ethanol Mandate (baseline)		
Transportation Sector (a)	9157	-2 (0.0%)	-332 (-3.6%)	-332 (-3.6%)
Crude oil Producers	79	0 (0.0%)	0 (0.0%)	0 (0.0%)
Gasoline consumers	5269	-2 (0.0%)	-206 (-3.9%)	-206 (-3.9%)
Diesel Consumers	3808	0 (0.0%)	-126 (-3.3%)	-126 (-3.3%)
Agricultural Sector (b)	4041	3 (0.1%)	-4 (-0.1%)	-1 (0.0%)
Agricultural Consumers	2573	-1 (0.0%)	1 (0.0%)	0 (0.0%)
Agricultural Producers	1467	4 (0.3%)	-5 (-0.3%)	-1 (-0.1%)
Government Revenue (c)	1047	0 (0.0%)	-19 (-1.8%)	-19 (-1.8%)
Total Welfare (a+b+c)	14244	1 (0.0%)	-355 (-2.5%)	-352 (-2.5%)
Panel B: Nitrate leaching and GHG emissions, 2035				
	Quantity	% change relative to Corn Ethanol Mandate (baseline)		
Nitrate leaching (million MT)	1.0	-10.0%	-5.7%	-10.0%
GHG emissions (billion MT)	1.9	-0.2%	-10.0%	-10.0%
Panel C: Nitrate tax and carbon tax, 2035				
Nitrate tax ($/kg)		5.3		1.7
Carbon tax ($/MT CO2e)			67.7	66.4

Note: NR10 refers to 10% Nitrate leaching Reduction; GHGR10 refers to 10% GHG emissions Reduction.

Table 7. Economic and environmental effects of imposing nitrate leaching and/or GHG emissions reduction targets in addition to the Corn & Cellulosic Ethanol Mandate

Scenario	Corn Ethanol Mandate (baseline) (1)	Corn & Cellulosic Ethanol Mandate (2)	Corn & Cellulosic Ethanol + NR10 (3)	Corn & Cellulosic Ethanol + GHGR10 (4)	Corn & Cellulosic Ethanol + NR10 & GHGR10 (5)
Panel A: Social welfare over 2016 – 2035 ($ billion)					
	Quantity	Absolute change (% change) relative to Corn Ethanol Mandate (baseline)			
Transportation Sector (a)	9157	-81 (-0.9%)	-82 (-0.9%)	-127 (-1.4%)	-125 (-1.4%)
Crude oil Producers	79	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Gasoline consumers	5269	-53 (-1.0%)	-53 (-1.0%)	-78 (-1.5%)	-76 (-1.4%)
Diesel Consumers	3808	-28 (-0.7%)	-28 (-0.7%)	-50 (-1.3%)	-49 (-1.3%)
Agricultural Sector (b)	4041	16 (0.4%)	18 (0.5%)	24 (0.6%)	24 (0.6%)
Agricultural Consumers	2573	-2 (-0.1%)	-3 (-0.1%)	-3 (-0.1%)	-3 (-0.1%)
Agricultural Producers	1467	18 (1.2%)	21 (1.4%)	27 (1.8%)	28 (1.9%)
Government Revenue (c)	1047	4 (0.4%)	4 (0.4%)	1 (0.1%)	1 (0.1%)
Total Welfare (a+b+c)	14244	-62 (-0.4%)	-60 (-0.4%)	-102 (-0.7%)	-99 (-0.7%)
Panel B: Nitrate leaching and GHG emissions, 2035					
	Quantity	% change relative to Corn Ethanol Mandate (baseline)			
Nitrate leaching (million MT)	1.0	-1.9%	-9.9%	-4.6%	-9.9%
GHG emissions (billion MT)	1.9	-6.6%	-7.1%	-10.0%	-10.0%
Panel C: Nitrate tax and carbon tax, 2035					
Nitrate tax ($/kg)			3.8		3.2
Carbon tax ($/MT CO2e)				38.1	37.9

Note: NR10 refers to 10% Nitrate leaching Reduction; GHGR10 refers to 10% GHG emissions Reduction.

4. Conclusions

This paper focuses on examining the economic and environmental impacts attributed to the imposition of two environmental reduction targets, nitrate runoff reduction and GHG emissions reduction, individually and jointly in addition to the corn ethanol mandate or corn and cellulosic ethanol mandates similar to the RFS on the agricultural and transportation sectors in the US. over the 2016–2035 period. We couple simulations from three biophysical models with a multi-period, multi-market, partial equilibrium, open-economy model (BEPAM) of the agricultural and transportation sectors to endogenously determine land allocation, food, and fuel, mix of cellulosic biofuels, consumption, and prices of achieving nitrate leaching and/or GHG emissions reductions beyond the levels that would be achieved by the implementation of the corn ethanol and cellulosic mandates. We also estimate and compare the costs of meeting these environmental reduction targets and analyze the cost-effectiveness of each policy design.

We find that the quantity-based corn and cellulosic ethanol blending mandates, like the RFS2, will reduce GHG emissions in 2035 due to replacing gasoline and diesel consumption with low carbon biofuels by 4.3% under the Corn Ethanol Mandate relative to the No-Policy scenario and additional 6.6% under the Corn & Cellulosic Ethanol Mandate; but increase the nitrate leaching by more than 10% than that under the No-Policy. The addition of a 10% nitrate leaching and/or GHG emissions reduction targets to the mandates is necessary to achieve desired environmental outcomes, which leads to land diversion from continuous corn to less C and N intensive corn-soybean rotation and also from row crops to energy crops, primarily in the MARB. Such land use effects are much larger under the scenarios of imposing a 10% Nitrate Policy or a 10% Combined Policy in addition to the biofuel mandate compared to that of imposing a 10% GHG Policy alone since the agricultural production is the major contributor to nitrate losses.

We also find that biofuel mandates raise the prices of fuels and crops, which lead to decreasing in consumers' benefits. We estimate that the Corn Ethanol Mandate will increase corn prices by 27% and soybeans price by 15% in 2035 relative to the No-Policy; the additional increases induced by the cellulosic ethanol mandate are much smaller (1% and 2%, respectively in 2035). We also find that a 10% reduction in nitrate leaching and/or GHG emissions, which are based on the amounts of leaching and emissions under the Corn Ethanol Mandate scenario, accompanying the Corn Ethanol Mandate or Corn & Cellulosic Ethanol Mandate will further increases corn price compared to the mandate alone. While the addition of these environmental targets to the Corn Ethanol Mandate will lead to a lower soybeans price by converting more productive land released from corn to produce soybeans relative to the Corn Ethanol Mandate alone, stacking the environmental targets on the Corn & Cellulosic Mandate will slightly increase soybeans price compared to the Corn & Cellulosic Mandate as it induce a shift towards producing energy crops that can provide multiple ecosystem benefits. Relative to the corn ethanol mandate or corn and cellulosic ethanol mandates alone, the increases in gasoline and diesel prices are almost negligible under the addition of a 10% Nitrate Policy to the biofuel mandates; while a 10% GHG Policy will significantly increase consumer prices of fossil fuels, e.g., the Corn Ethanol + GHGR10 will lead to a 25% increase in gasoline price and 34% in diesel price than that of the Corn Ethanol Mandate.

Our results show that compared to the biofuel mandate alone, the addition of the10% nitrate leaching reduction to the mandate shows minor impacts on social welfare; while the addition of the 10% GHG emissions reduction creates a larger welfare loss as the reduction in fuel consumers' benefits due to increased fuel prices far outweigh the gains in the agricultural sector. Specifically, we estimate the economic cost of supplementing the Corn Ethanol Mandate with a 10% GHG reduction will be $ 355 billion over 2016-2035. It will also reduce gasoline consumption by more than 9.7% and diesel consumption by 7.2% in 2035, relative to the Corn Ethanol Mandate scenario. Imposing a 10% Combined Policy in addition to the mandate shows similar effects to that of the addition of a 10% GHG Policy. The implementation of the cellulosic mandate will lead to higher agricultural producers' benefits than the Corn Ethanol Mandate by $18 billion and $81 billion lower fuel consumers' benefits. However, it will lead to higher GHG savings (6.6%) in 2035 relative to the Corn Ethanol Mandate. An additional 3.4% GHG emissions reduction target stacked to the cellulosic ethanol mandate increases the production of cellulosic ethanol by 15%, although the overall social cost will be increased by $41 billion compared to the cellulosic ethanol mandate alone.

We find that either a nitrate tax or a carbon tax can achieve a reduction in nitrate runoff and in GHG emissions jointly. The nitrate tax needed to supplement a biofuel mandate to achieve a 10% reduction in nitrate runoff is higher than that of stacking a 10% Combined Policy on a biofuel mandate and it is accompanied by a smaller reduction in GHG emissions but the welfare cost of a 10% Nitrate Policy is substantially lower than that of a 10% Combined Policy (relative to the Corn Ethanol Mandate scenario). For example, the nitrate tax needed is two times larger under the Corn Ethanol + NR10 than that under the Corn Ethanol + NR10 & GHG10, with a 0.2% GHG emissions reduction in 2035 as the co-benefit; while imposing a 10% Nitrate Policy in addition to the Corn Ethanol Mandate leads to a lower welfare cost by $356 billion relative to the addition of a 10% Combined Policy to the mandate. Moreover, achieving a 10% reduction in GHG emissions through accompanying a biofuel mandate with a carbon tax alone is less cost-effective than supplementing a biofuel mandate with a combined carbon tax and nitrate tax to decrease both nitrate leaching and GHG emissions by 10% because stacking the 10% GHG Policy alone on a biofuel mandate will lead to a higher carbon tax and welfare cost, as well as a far less than 10% reduction in nitrate leaching as a complement.

Our analysis relies on a simplifying assumption that the effects of land use change on nitrate losses are exogenously determined with certainty. In reality, nitrate runoff varies by soil, management, weather conditions and other factors that are uncertain. As a result, it may be more appropriate to specify probabilistic goals for water quality and examine the costs of achieving them with a given probability. We leave it to future research to analyze the implications of different uncertainties for policy design. We also do not consider other benefits associated with reductions in nitrate leaching and GHG emissions, such as higher profits to commercial fisheries due to improved water quality and supporting wildlife biodiversity. We leave this area for future research to examine.

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Supporting Information

Table S1. Agricultural Sector Model Validation

	Observed Data				Model Simulation				Diff%			
	2016	**2017**	**2018**	**2019**	**2016**	**2017**	**2018**	**2019**	**2016**	**2017**	**2018**	**2019**
Panel A: Land allocation (M acres)												
Land under corn	94	90	89	90	88	91	91	90	-7%	1%	2%	0%
Land under soybeans	82	90	89	77	87	83	84	84	6%	-8%	-5%	9%
Land under wheat	47	45	47	45	43	41	40	41	-10%	-9%	-14%	-9%
Panel B: Crop price (\$ Mg^{-1})												
Corn	137	133	138	141	153	158	160	156	12%	19%	16%	10%
Soybeans	338	346	328	313	347	347	352	345	3%	0%	7%	10%
Wheat	161	158	182	179	178	179	176	176	11%	13%	-3%	-2%

Table S2. Fuel Sector Model Validation

	Observed Data				Model -- Xinxin				Diff% -- Xinxin			
	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Panel A: Fuel gallons (M gallon)												
US oil consumption	248,825	254,320	260,141	253,907	236,607	236,607	236,607	236,607	-5%	-7%	-9%	-7%
US oil supply	136,066	143,663	168,079	187,762	137,516	137,516	137,516	137,516	1%	-4%	-18%	-27%
ROW Oil use	1,125,476	1,131,962	1,175,515	1,196,158	1,136,145	1,136,145	1,136,145	1,136,145	1%	0%	-3%	-5%
ROW Oil supply	1,238,235	1,242,619	1,267,576	1,262,303	1,235,236	1,235,236	1,235,236	1,235,236	0%	-1%	-3%	-2%
US gasoline consumption	109,243	109,055	109,083	108,854	101,123	103,458	105,282	107,000	-7%	-5%	-3%	-2%
US diesel consumption	51,257	51,841	54,658	54,099	47,813	48,877	48,267	49,510	-7%	-6%	-12%	-8%
US gas export	6,757	8,384	9,752	8,430	7,858	5,524	3,699	1,982	16%	-34%	-62%	-76%
US diesel export	15,869	18,866	17,076	16,916	11,197	10,133	10,743	9,500	-29%	-46%	-37%	-44%
Panel C: Vehicle miles traveled												
Gasoline vehicle miles	2,407,782	2,518,247	2,551,656	2,576,906	2,453,631	2,545,098	2,619,540	2,694,406	2%	1%	3%	5%
Diesel vehicle miles	410,056	414,730	437,262	432,793	391,603	405,310	407,336	421,593	-4%	-2%	-7%	-3%

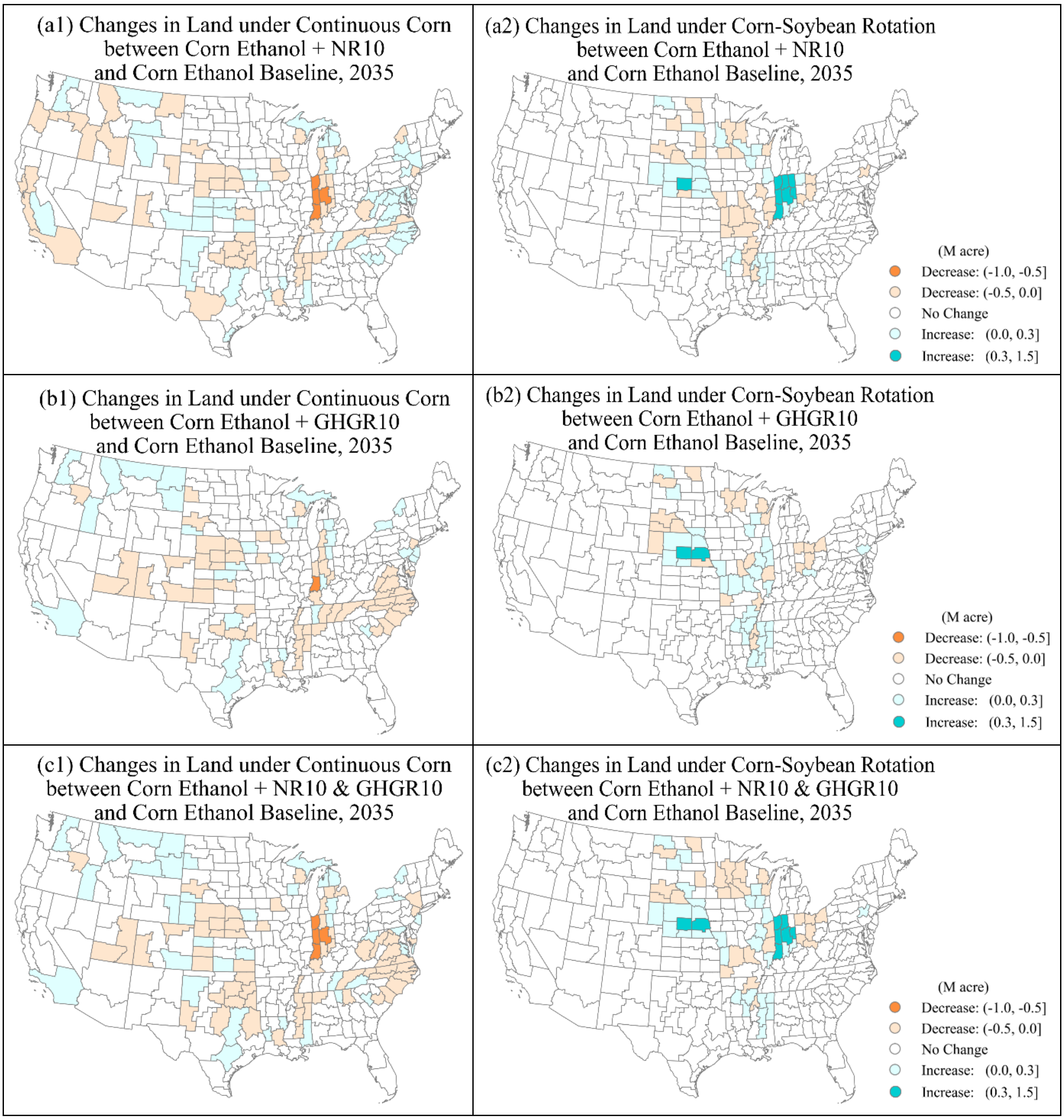

Figure S1. Changes in land under continuous corn or corn-soybean rotation in 2035 (M acre) simulated under three policy scenarios: supplementing corn ethanol mandates with a 10% reduction in nitrate runoff (Corn Ethanol + NR10); supplementing corn ethanol mandates with a 10% reduction in GHG emissions (Corn Ethanol + GHGR10); supplementing corn ethanol mandates with a 10% reduction in both nitrate runoff and GHG emissions (Corn Ethanol + NR10 & GHGR10) relative to Corn Ethanol Mandate scenario (the baseline).

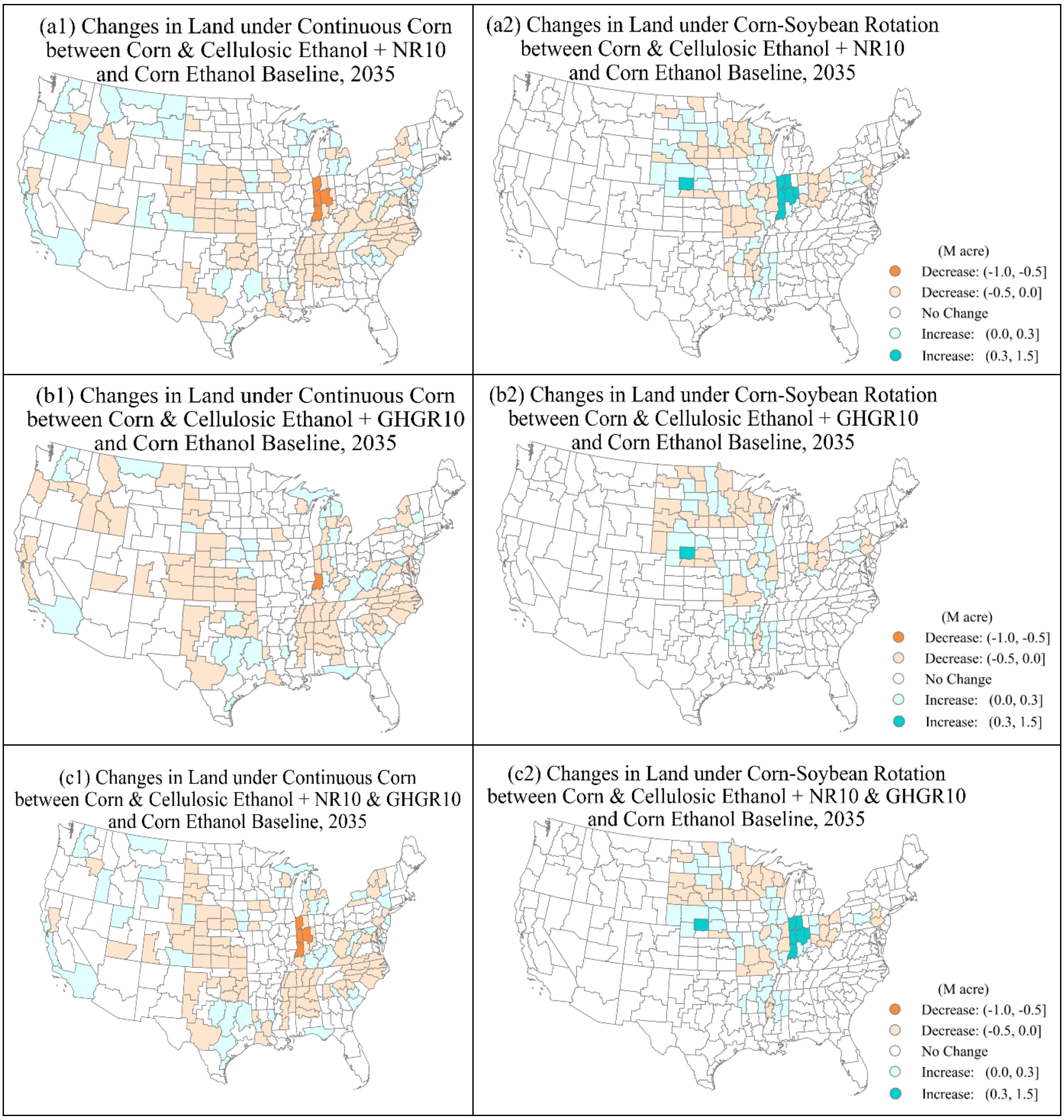

Figure S2. Changes in land under continuous corn or corn-soybean rotation in 2035 (M acre) simulated under three policy scenarios: supplementing corn and cellulosic ethanol mandates with a 10% reduction in nitrate runoff (Corn & Cellulosic Ethanol + NR10); supplementing corn and cellulosic ethanol mandates with a 10% reduction in GHG emissions (Corn & Cellulosic Ethanol + GHGR10); supplementing corn and cellulosic ethanol mandates with a 10% reduction in both nitrate runoff and GHG emissions (Corn & Cellulosic Ethanol + NR10 & GHGR10) relative to Corn Ethanol Mandate scenario (the baseline).

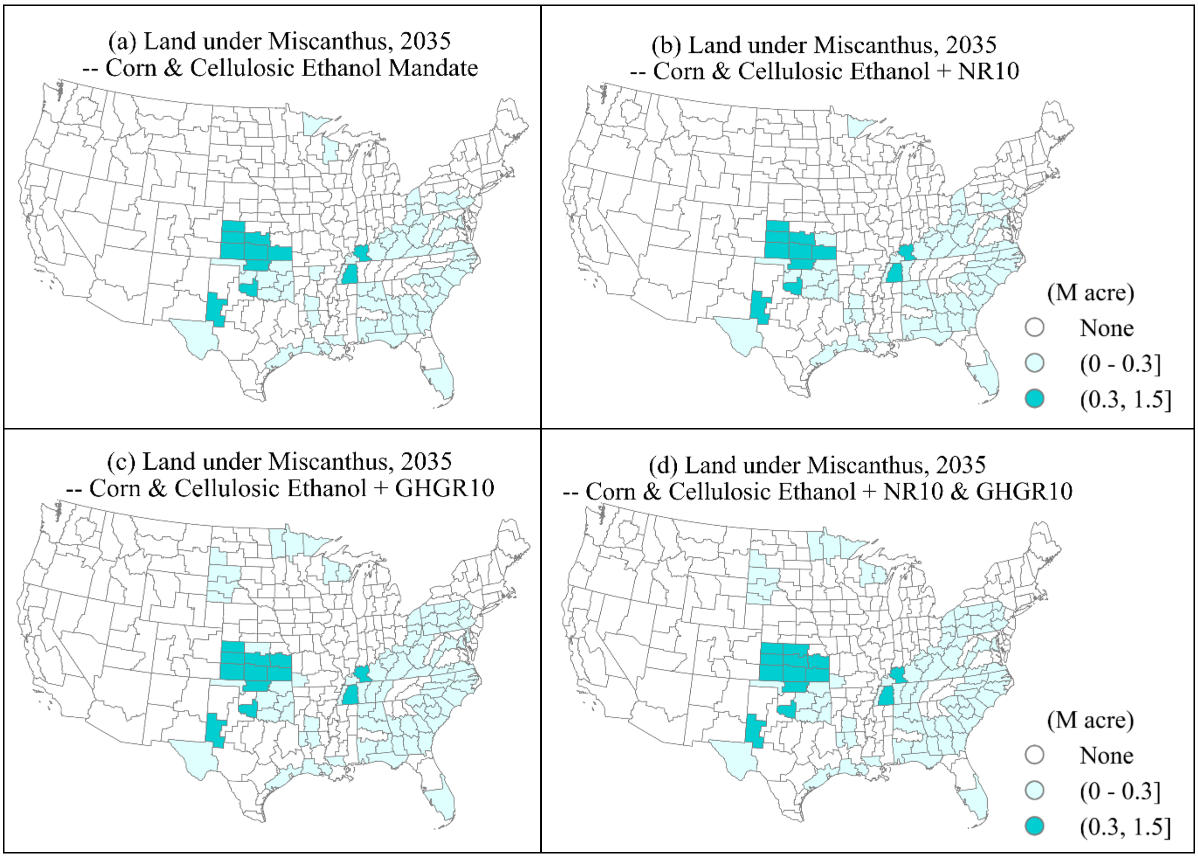

Figure S3. Land under miscanthus in 2035 (M acre) simulated under three policy scenarios: supplementing corn and cellulosic ethanol mandates with a 10% reduction in nitrate runoff (Corn & Cellulosic Ethanol + NR10); supplementing corn and cellulosic ethanol mandates with a 10% reduction in GHG emissions (Corn & Cellulosic Ethanol + GHGR10); supplementing corn and cellulosic ethanol mandates with a 10% reduction in both nitrate runoff and GHG emissions (Corn & Cellulosic Ethanol + NR10 & GHGR10).

Table S3. Effects of alternative biofuel mandates on the agricultural sector in 2035.

Scenario	No-Policy (1)	Corn Ethanol Mandate (2)	Corn & Cellulosic Ethanol Mandate (3)
Panel A: Land allocation by crop (million ha)			
Row crops (a)	Quantity	% change relative to No-Policy	
Corn (MARB)	23.8	19.2%	16.3%
Corn (non-MARB)	5.7	12.2%	10.3%
Soybeans (MARB)	27.8	-0.2%	-0.8%
Soybeans (non-MARB)	6.1	17.1%	12.3%
Wheat (MARB)	9.9	9.1%	4.4%
Wheat (non-MARB)	6.5	-2.4%	-2.7%
Other crops (MARB)	12.9	5.8%	2.5%
Other crops (non-MARB)	13.3	-1.0%	-0.8%
Energy crop (b)			
Miscanthus (MARB)		--	2.7
Miscanthus (non-MARB)		--	1.5
Total land under crop production (a+b)	106.1	7.2%	9.2%
Panel B: Land allocation by rotation (million ha)			
	Quantity	% change relative to No-Policy	
Continuous corn (MARB)	11.3	16.5%	11.7%
Conventional tillage	0.9	2.9%	5.9%
No-till	10.5	17.6%	12.1%
Continuous corn (non-MARB)	3.2	11.2%	7.9%
Conventional tillage	0.0	--	--
No-till	3.2	11.2%	7.9%
Corn-Soybean rotation (MARB)	24.9	21.7%	20.6%
Conventional tillage	13.9	13.8%	-21.1%
No-till	11.0	31.8%	73.4%
Corn-Soybean rotation (non-MARB)	5.2	13.4%	11.7%
Conventional tillage	2.8	-29.1%	-48.5%
No-till	2.4	63.7%	83.0%
Panel C: Row Crop Price ($/MT)			
	Price	% change relative to No-Policy	
Corn	109.0	26.9%	27.6%
Soybeans	279.9	15.3%	17.4%
Wheat	191.5	-5.7%	-1.2%

Table S4. Effects of alternative biofuel mandates on the transportation sector in 2035.

Scenario	No-Policy (1)	Corn Ethanol Mandate (baseline) (2)	Corn & Cellulosic Ethanol Mandate (3)
Panel A: Fuel Consumption (billion gallons)			
	Quantity		
Diesel	54.8	53.3 (-2.8%)	52.6 (-4.0%)
Gasoline	101.8	94.2 (-7.5%)	82.5 (-19.0%)
Corn Ethanol	5.8	14.6	13.7
			Quantity
Cellulosic Ethanol			16.0
from corn stover			8.6
from miscanthus			7.1
Panel B: Consumer fuel prices (US) ($/gallon)			
	Price		
Diesel	2.15	2.24 (4.2%)	2.38 (10.4%)
Gasoline	2.40	2.51 (4.7%)	2.63 (9.7%)
Corn ethanol	2.56	2.76 (8.1%)	2.77 (8.1%)
Cellulosic ethanol			3.3
Panel C: Vehicle kilometers traveled (billion km)			
	Quantity		
Diesel	900.5	893.2 (-0.8%)	882.3 (-2.0%)
Gasoline	4789.7	4713.1 (-1.6%)	4638.9 (-3.1%)
Panel D: Price of vehicle kilometers traveled ($/km)			
	Quantity		
Diesel	0.133	0.139 (4.2%)	0.147 (10.4%)
Gasoline	0.053	0.056 (4.6%)	0.058 (8.8%)

Note: Percentage changes are in parenthesis of column (2) and (3) refer to changes in the Corn Ethanol Mandate and Corn & Cellulosic Ethanol Mandate scenario relative to that under the No-Policy scenario, respectively.