Energy Policy 175 (2023) 113497

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Reducing US biofuels requirements mitigates short-term impacts of global population and income growth on agricultural environmental outcomes

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ABSTRACT

Biobased energy, particularly corn starch-based ethanol and other liquid renewable fuels, is a major element of federal and state energy policies in the United States. These policies are motivated by energy security and climate change mitigation objectives, but corn ethanol does not substantially reduce greenhouse gas emissions when compared to petroleum-based fuels in all production scenarios. Corn production also imposes substantial negative externalities (e.g., nitrogen leaching, higher food prices, water scarcity, and indirect land use change). In this paper, we utilize a partial equilibrium model of corn-soy production and trade to analyze the potential of reduced US demand for corn as a biobased energy feedstock to mitigate increases in nitrogen leaching, crop production and land use associated with growing global populations and income from 2020 to 2050. We estimate that a 24% demand reduction would sustain land use and nitrogen leaching below 2020 levels through the year 2025, and a 41% reduction would do so through 2030. Outcomes are similar across major watersheds where corn and soy are intensively farmed.

1. Introduction

Biofuels are an important component of United States energy and climate change mitigation policies. Forty-one states have adopted Renewable Portfolio Standards mandating minimal levels of electricity production from renewable sources for which at least one form of biomass qualifies (National Conference of State Legislatures, 2021). At the federal level, a Renewable Fuel Standard (RFS2) was first legislated in the Energy Policy Act of 2005 (US Federal Register, 2005) and expanded in the Energy Independence and Security Act of 2007 (US Federal Register, 2007). These policies commonly mention energy security and economic development as motivators, but a key operational requirement of RFS2 is that qualifying renewable fuels should have lower life cycle greenhouse gas (GHG) emissions than the petroleum fuels they substitute for in the market. Production targets are set for various types of liquid renewable fuels with differing emissions requirements. To this end, corn starch-based ethanol (henceforth, “corn ethanol”) and other conventional biofuels are expected to comprise well over half of RFS2’s final volume requirement of 20.63 billion gallons of ethanol-equivalents for 2022 (US Environmental Protection Agency, 2022).

However, a recent review concluded that the use of corn ethanol has limited capacity to reduce greenhouse gas emissions, with studies that accounted for land use change estimating it produces on average about 75% of the life cycle GHG emissions of petrol and diesel (Jeswani et al., 2020); not all of the studies included in this average included both direct and indirect land use change, however, so the average may be higher if both were accounted for in all the production scenarios modeled in the reviewed studies. Methods for producing such estimates, in particular of greenhouse gas emissions due to land use change, are controversial, however (Lark et al., 2022a, 2022b; Scully et al., 2021; Spawn-Lee et al., 2021; Taheripour et al., 2022). Sanchez et al. (2018) concludes that the greenhouse gas emissions resulting from fermentation of corn ethanol can be substantially mitigated via subsidized carbon capture and sequestration, but the aforementioned controversy over land use change emissions makes the relative importance of these findings unclear. Fertilizer applied to increase corn yields exacerbates hypoxic “dead zones” in the ocean, chiefly the Gulf of Mexico (Diaz and Rosenberg, 2008; Rabalais and Turner, 2019), and leads to harmful algal blooms in the Great Lakes (Brooks et al., 2016; Smith et al., 2015; Watson et al., 2016). Liu et al. (2018) examine multiple interventions designed to meet the Hypoxia Task Force’s target of a 45 percent reduction in nitrogen and phosphorus fluxes to the Gulf of Mexico (US EPA, 2016), concluding that no single measure can effectively reach that goal. VanLoocke et al. (2017) find that conversion of even 40% of land devoted to corn ethanol feedstock in the Mississippi-Atchafalaya River Basin to miscanthus

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https://doi.org/10.1016/j.enpol.2023.113497
Received 15 July 2022; Received in revised form 9 February 2023; Accepted 13 February 2023
Available online 25 February 2023
0301-4215/

would only reduce nitrogen runoff by 5–15%.

Biobased energy feedstock production increases demand for agricultural land, which leads to increased deforestation globally (Busch and Ferretti-Gallon, 2017) and likely to substantial net carbon emissions associated with indirect land use change, given the conclusions of Chen and Khanna (2018) that expansion of US corn ethanol production from 2007 to 2012 led to "conversion of 3.2 million acres of unused cropland, including 1 million acres in [the US Conservation Reserve Program], to crop production." As a result of the same dynamics, corn-based biofuel production may also lead to an increase in global food prices (Carter et al., 2017; Hochman and Zilberman, 2018; Kocak et al., 2022), thereby worsening global malnutrition, which remains a serious issue globally (Black et al., 2008; Gómez et al., 2013; Perez-Escamilla et al., 2018)[1]. The water required to grow corn for biofuels also imposes negative environmental impacts, given serious water scarcity in some intensively cultivated regions of the United States (Shah et al., 2007); the water intensity of corn ethanol production is further expected to increase due to climate change (Dominguez-Faus et al., 2013). Finally, expansion of agricultural area and intensification of production on existing cropland leads to reduced biodiversity and ecosystem services, albeit in a complex fashion (Seppelt et al., 2016). To summarize, RFS2 calls for production of corn ethanol which imposes many environmental costs which weigh against its contributions to climate change mitigation objectives.

All of these negative externalities are likely to be exacerbated by projected population and income growth, leading to greater demand for agricultural outputs (Riahi et al., 2017). In this paper, we examine the potential for reductions to conventional biofuels production associated with the RFS2 mandate to mitigate the short-term environmental stressors of agricultural demand growth imposed by population and income growth. Our analysis utilizes a Gridded version of the Simplified International Model of agricultural Prices, Land use, and the Environment (SIMPLE-G) focusing on corn and soy production in the United States (SIMPLE-G-US-CS). SIMPLE-G is a partial equilibrium modeling framework for agricultural production and trade that can be used to evaluate agricultural policies while representing the heterogeneity of natural resources and productivity at high resolution (Baldos et al., 2020). Liu et al. (2022) used the SIMPLE-G-US-CS model to examine the potential for various nitrogen management interventions to reduce leaching within the Mississippi River Basin, underscoring the need for high-resolution gridded analysis.

However, we stress that repeal of RFS2 mandates would not eliminate demand for corn ethanol. Babcock (2013) estimated an incremental 13.5% increase in demand for corn ethanol from RFS2, which Carter et al. (2017) argues actually represents an upper bound on the decrease that would be associated with its repeal. Moschini et al. (2017) instead estimates that repeal of RFS2 in 2015 would have resulted in a reduction of 71% in corn ethanol production (still under an assumption that a minimum of 3% of blended gasoline fuel is ethanol used as a gasoline oxygenate due to technological requirements). Currently, about 40% of corn grown in the US is used by corn ethanol production ("USDA ERS - Feedgrains Sector at a Glance," n. d.). The Biden administration's waiver in April 2022 allowing gasoline to be blended with up to 15% ethanol from June 1 to September 15 (when it is typically restricted in the US due to air quality concerns) (US EPA, 2022a), and subsequent increase in the corn ethanol volume required to be blended into gasoline in 2022 (US EPA, 2022b), illustrate the deep uncertainty in the actual demand reduction that would result from repeal of RFS2. In this paper, we therefore frame the results as an analysis of the outcomes associated with reduced US demand for corn ethanol, rather than the direct result of policy repeal.

Many of the studies cited here incorporate similar general or partial equilibrium models in their methodology to what we present in this analysis. Most commonly these examine the effects of RFS2 standards on prices, production or land use change, although Lark et al. (2022b) and its ensuing responses also covers fertilizer use and water quality outcomes. In this paper, we explore environmental outcomes from the opposite direction, identifying the impacts of demand reductions of various magnitudes amidst future changes to global population, incomes, and productivity.

2. Methods

For this analysis, we employ a gridded version of the Simplified International Model of agricultural Prices, Land use, and the Environment (SIMPLE-G) (Baldos et al., 2020). This version, SIMPLE-G-US-CS, focuses on corn and soy production in the United States. The model is calibrated to a baseline year of 2010 and validated by hindcasting over the period 1990–2006. However, key parameters relevant to this analysis, such as nitrogen application rates, nitrate leaching rates and substitution elasticities between nitrogen fertilizer and other inputs, are taken from more recent estimates used by the Agro-IBIS biogeochemical crop model (Lark et al., 2022b; Liu et al., 2022; Sun et al., 2020). SIMPLE-G-US-CS is a partial-equilibrium modeling framework for agricultural production and trade which can be used to evaluate agricultural policies while representing the spatial heterogeneity of natural resources and productivity at high resolution. Grid cells in the contiguous US are spaced at a 5 arc-minute resolution, with the rest of the world represented by 15 non-gridded regions (denoted in Fig. 1).

In SIMPLE-G-US-CS, baseline acreages of corn and soy production in each grid cell are derived from downscaling national data using the spatial pattern provided by the USDA Crop Data Layer (CDL) data set. Production, inputs and outputs of the model are aggregated over the two crops to a corn-soy composite, where use of the CDL data set implicitly means that this composite reflects current practices associated with corn-soy rotations and continuous cropping. Separate acreages are specified for irrigated and rainfed production, and different transfer functions are used describing the relationship between nitrogen fertilizer application and yield for irrigated and rainfed areas. The yield transfer functions in Gompertz form are fitted to the pairs of nitrogen fertilizer application rate and the corresponding crop yield simulated by Agro-IBIS (Kucharik, 2003; Sacks and Kucharik, 2011). Similarly, leaching transfer functions in quadratic form are built into SIMPLE-G-US-CS to capture the nonlinear leaching response to various intensity of nitrogen fertilizer application (Lark et al., 2022c). More details about the SIMPLE-G-US-CS model can be found in supplementary materials and Liu et al. (2022).

Projections of population, income and total factor productivity growth, by region, correspond to Shared Socioeconomic Pathway 2 (SSP2), the IPCC's "Middle of the Road" pathway; population and income growth paths are shown in Fig. 1 (Riahi et al., 2017; O'Neill et al., 2014). Biofuels demand projections in the rest of the world are aggregated regionally from the International Energy Agency's 2020 World Energy Outlook (International Energy Agency, 2020). RFS2 biobased energy mandates, as well as biofuels demand in other regions, are modeled as exogenous demand shocks, consistent with the implementation of other parameters varied in our experimental design. We modeled these changes in the years 2020–2050 at five-year intervals, combined with reductions in US biobased energy feedstock demands from 0% (i.e., no change) to 50% at 1-percent intervals. Total factor productivity changes for livestock, crops, and processed foods are taken from future projections from Ludena et al. (2007), and historical estimates from USDA-ERS (2021) and Griffith et al. (2004), respectively. Ultimately, we focus on discussing short-term impacts from 2020 to 2030, when population and other projections are less uncertain, justifying the use of a single SSP trajectory.

Gridded outputs from the SIMPLE-G-US-CS model were captured for land use (i.e., acreage of land under corn-soy production in each grid cell), corn-soy production, and associated nitrogen leaching. We also recorded the equilibrium corn-soy prices as calculated in each region (these are summarized in Supplementary Table S1).

We note that while our analysis uses a 2020 baseline for comparing results in the other years, model outputs for 2020 are themselves

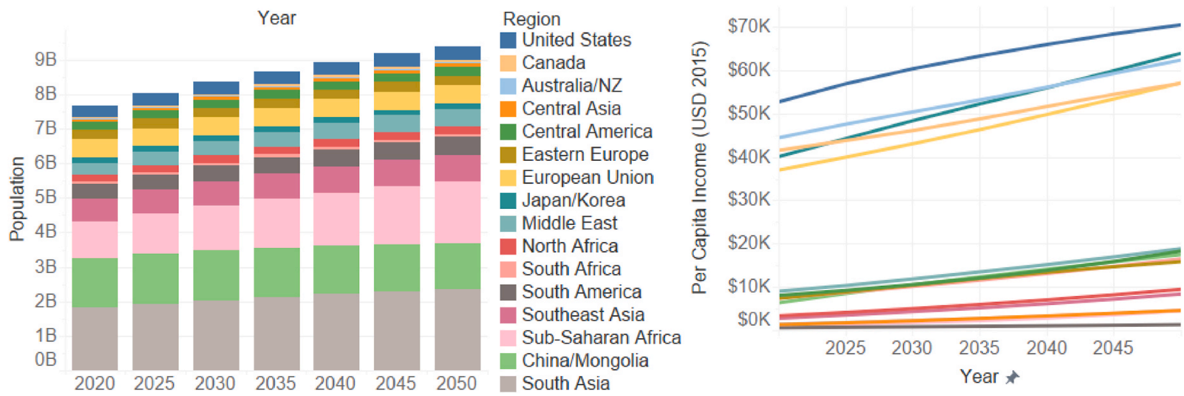

Fig. 1. Population over time (left) and per capita income (right), 2020–2050, SSP2, aggregated by SIMPLE-G-US-CS region (source data: Riahi et al. (2017)).

projected forward from the model's calibrated 2010 base assumptions. We have not made adjustments to projected input parameters in 2020, or other years, related to the COVID-19 pandemic. While this represents a limitation to some extent, we find it justified given that global agricultural trade "fell 2 percent in 2020Q2 during the initial wave of COVID-19 infections and lockdowns," but "rebounded significantly during 2020Q3 and 2020Q4 and ended the year up" (Arita et al., 2022). The pandemic's overall impact on agricultural trade, while varied across the world, has been substantially smaller than that of other events such as the Great Recession of 2007–2009 and the trade dispute between the United States and China in 2018 that led to multiple rounds of tariffs (Arita et al., 2022). Haqiqi and Bahalou Horeh (2021) estimate the reduction in total US farm outputs attributable to COVID-19 in 2020 to be 2.6%.

3. Results and discussion

Aggregate US outcomes for land use, corn-soy production, and nitrogen leaching are presented in two different forms to highlight the role of corn ethanol demand reductions in future outcomes. Fig. 2 presents the projections for growth in land use, production and leaching, relative to the 2020 benchmark. Fig. 3 isolates the effect of the demand reductions by comparing future outcomes to a business-as-usual case, with 0% representing the *status quo* (i.e., no change to RFS2) and additional traces showing the deviations owing to RFS2 policy actions. For visual clarity, traces are only shown for demand reductions from 5 to 50 percent, at 5 percent intervals. We see total production and leaching outcomes that have similar sensitivity to biofuels demand reductions, with elasticities of approximately 0.4 and 0.5, respectively (i.e., a 10% reduction in the demand reduces production by 4% and leaching by about 5%). Land use is considerably less sensitive, with an elasticity of approximately 0.2.

The capacity for RFS2 changes (or other policy mechanisms impacting ethanol demand) to mitigate the short-term impacts of population and income growth depends not only on the elasticity but on the current trends in environmental outcomes. In order to keep nitrogen leaching and land use below their 2020 levels by the year 2025, repeal would need to result in a demand reduction of at least 24%; under these demand reductions, overall corn-soy production in 2025 would still increase by 4.2%. To maintain nitrogen leaching and land use below their 2020 levels until the year 2030 would require a demand reduction of at least 41%; in this scenario, corn-soy production in 2025 would be 4.4% less than 2020 levels but 9% higher than 2020 levels in 2030.

When compared to outcomes in a *status quo* future, production, leaching, and land use all decline in response to a reduction in biofuels demand, with the proportional difference generally increasing over time. The difference grows more quickly in the first decade than from 2030 to 2050, although the distinction is slight; change in the difference over time is approximately linear.

The geospatial pattern of differences in outcomes is consistent across metrics and years, with selected results shown in Figs. 4 and 5. These figures depict nitrogen leaching outcomes in 2030, 2040, and 2050 associated with demand reductions of 24% and 41%, the reductions associated with maintaining leaching and land use outcomes below 2020 levels until 2025 and 2030, respectively. One interesting finding is that the areas with the greatest reduction in leaching when compared to the *status quo*, such as southwest Kansas and near the Appalachian Mountains, are the same areas with the largest leaching increases when expressed as a percentage of 2020 levels. These are marginal areas which have proven sensitive to demand fluctuations in the past (Lark et al., 2015).

Despite the limited spatial heterogeneity of outcomes in intensively

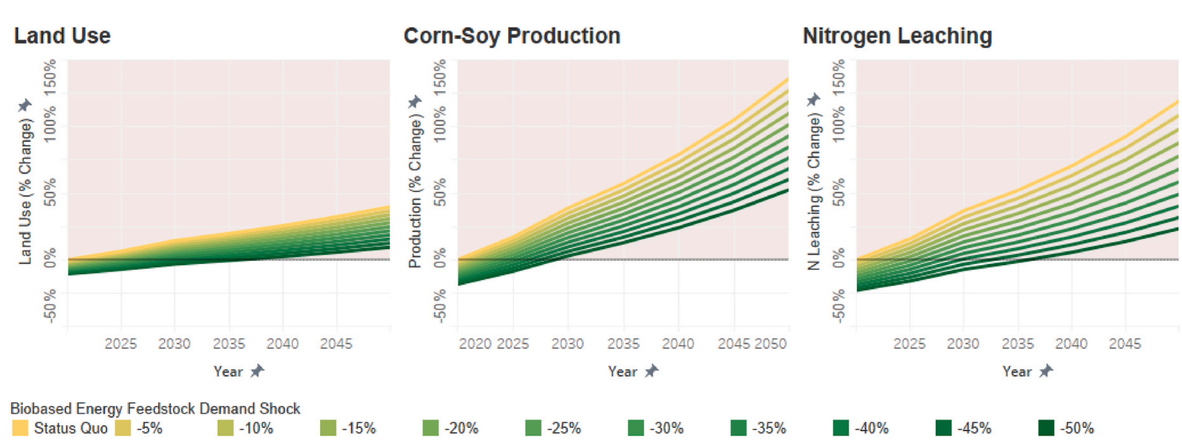

Fig. 2. Aggregated United States outcomes for corn-soy land use, production and leaching in the continental US, 2020–2050, relative to 2020 levels.

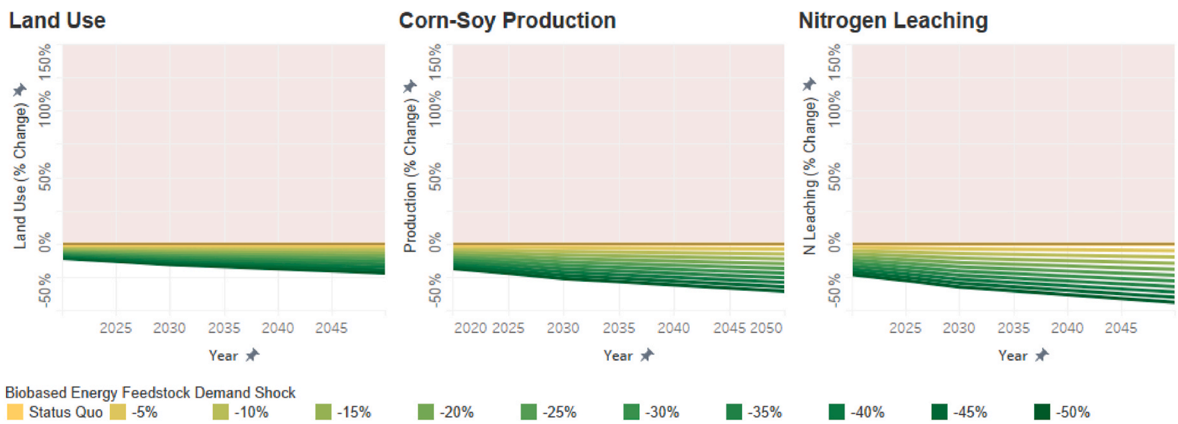

Fig. 3. Aggregated United States outcomes, 2020–2050, relative to *status quo*..

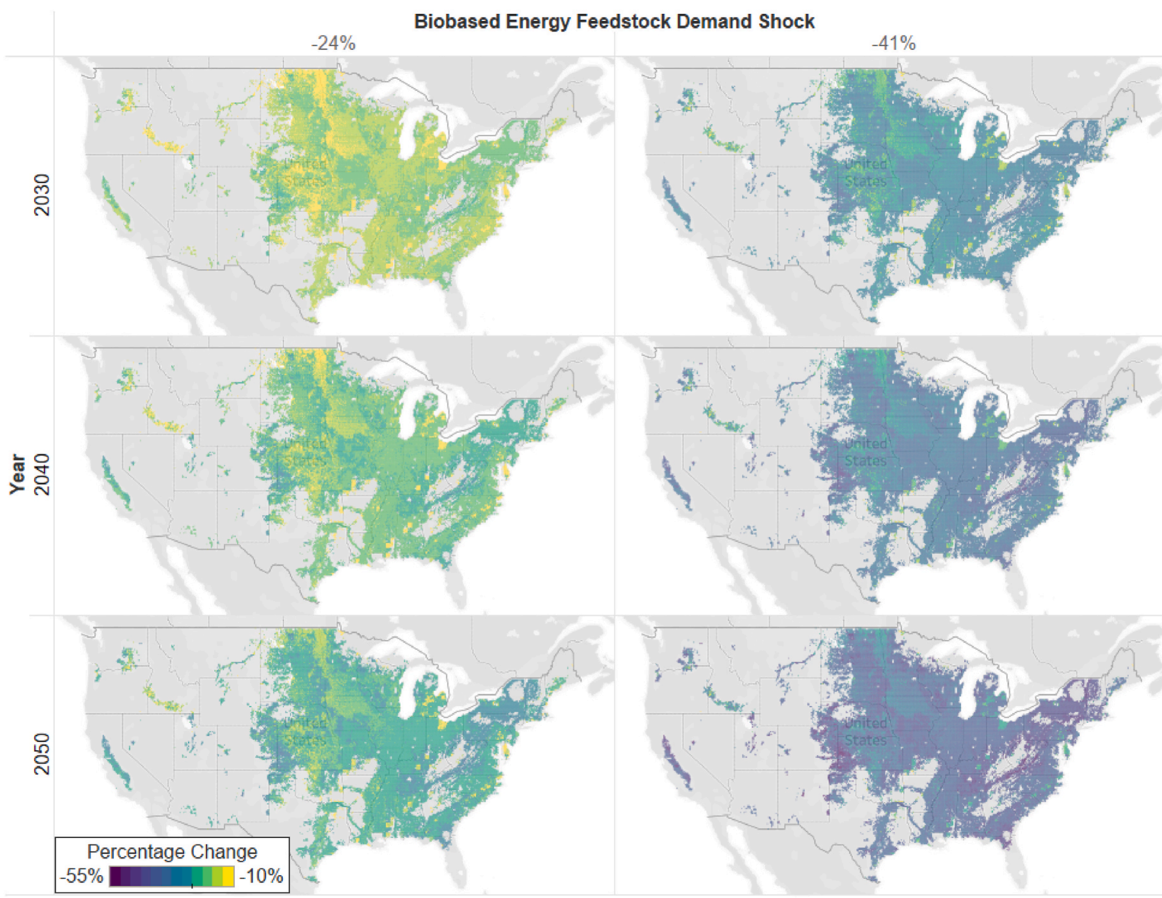

Fig. 4. Change in nitrogen leaching from corn-soy production with selected demand shocks, 2030 to 2050, relative to *status quo*..

farmed regions, it is nonetheless of interest to summarize the results by major basin, particularly nitrogen leaching which contributes to significant leachate exports to key water bodies (Ator et al., 2020; Ator and Denver, 2015; Mooney et al., 2020; Sun et al., 2020). Table 1 and Table 2 present the land use, corn-soy crop production, and nitrogen leaching over time, expressed both relative to the *status quo* and as a percentage of 2020 levels, respectively, in the Mississippi River Basin, Great Lakes Basin, and Chesapeake Bay. From these results, it is clear to see, for example, that even a large 41% reduction in US demand for biobased energy feedstocks will not by itself meet the Hypoxia Task Force's target 45% reduction in nitrogen fluxes to the Gulf of Mexico from the Mississippi River. Demand reductions have the greatest impact in the Chesapeake Bay region, followed by the Mississippi River and Great Lakes, although the differences across basins are not substantial.

4. Conclusions and limitations

Fig. 2 illustrates the large increases from 2020 to 2050 in US corn-soy production, associated land use and nitrogen leaching projected under population and income changes corresponding to the SSP2 scenario. This poses a substantial challenge to the prospects of meeting environmental goals, such as reducing nitrogen fluxes to the Gulf of Mexico to manage the hypoxic zone. We have discussed estimates of corn-soy demand reduction that may be needed to meet certain policy goals,

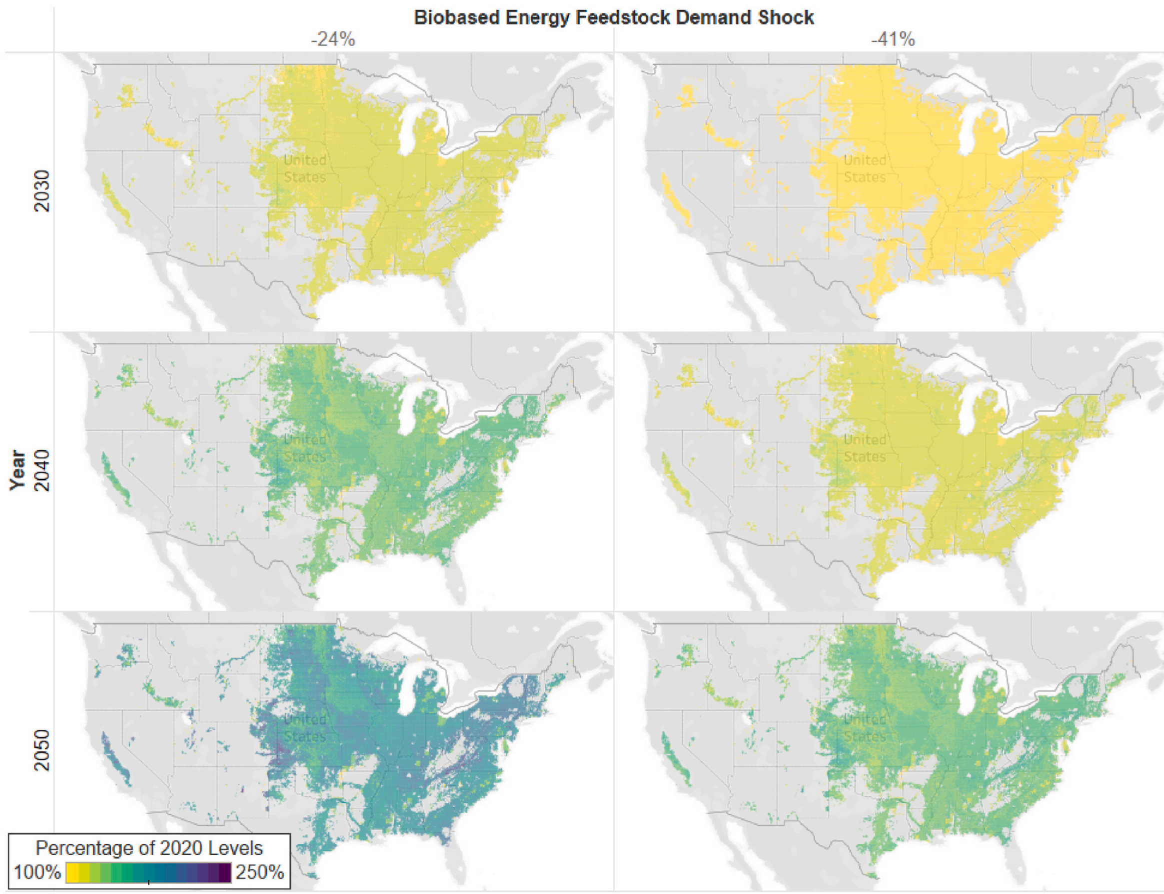

Fig. 5. Nitrogen leaching with selected demand shocks, 2030 to 2050, as a percentage of 2020 levels.

Table 1
Changes in outcomes in selected basins resulting from 24% to 41% demand reductions, relative to *status quo*.

		Biobased Energy Feedstock Demand Shock/Year					
		−24%			−41%		
		2030	2040	2050	2030	2040	2050
Mississippi River	Land Use	−7.5%	−8.9%	−10.3%	−12.8%	−15.3%	−17.9%
	Crop Production	−12.9%	−15.2%	−17.5%	−21.5%	−25.5%	−29.4%
	Nitrogen Leaching	−16.6%	−19.6%	−22.6%	−27.2%	−32.2%	−37.0%
Great Lakes	Land Use	−7.0%	−8.4%	−9.8%	−11.9%	−14.4%	−16.9%
	Crop Production	−12.6%	−15.0%	−17.3%	−21.0%	−25.0%	−29.0%
	Nitrogen Leaching	−15.8%	−18.9%	−21.9%	−26.0%	−30.9%	−35.9%
Chesapeake Bay	Land Use	−8.1%	−9.7%	−11.4%	−13.7%	−16.6%	−19.5%
	Crop Production	−14.0%	−16.6%	−19.3%	−23.2%	−27.6%	−31.9%
	Nitrogen Leaching	−16.7%	−20.1%	−23.5%	−27.4%	−32.7%	−38.1%

Table 2
Changes in outcomes in selected basins resulting from 24% to 41% demand reductions, as a percentage of 2020 levels.

		Biobased Energy Feedstock Demand Shock/Year					
		−24%			−41%		
		2030	2040	2050	2030	2040	2050
Mississippi River	Land Use	106.0%	114.7%	125.8%	99.9%	106.7%	115.2%
	Crop Production	121.0%	151.7%	194.9%	109.0%	133.4%	166.8%
	Nitrogen Leaching	114.5%	137.5%	170.7%	99.9%	116.1%	139.0%
Great Lakes	Land Use	105.6%	113.6%	123.9%	99.9%	106.1%	114.1%
	Crop Production	120.6%	150.8%	193.1%	109.0%	133.0%	165.8%
	Nitrogen Leaching	113.6%	135.2%	166.3%	99.9%	115.1%	136.6%
Chesapeake Bay	Land Use	106.4%	115.9%	128.2%	99.9%	107.1%	116.5%
	Crop Production	122.0%	155.0%	202.4%	109.0%	134.7%	170.6%
	Nitrogen Leaching	114.5%	137.7%	172.0%	99.9%	116.1%	139.3%

showing that these fall beyond the realm of likely responses to RFS2 repeal: with an estimated nitrogen leaching elasticity of demand of approximately 0.5, even a 50% reduction in corn ethanol demand would reduce leaching by only approximately 25% relative to 2020 levels (Fig. 3). Leaching reductions are not wholly realized as reductions in nitrogen fluxes to the Gulf of Mexico, due to processes like aquatic nutrient decay in streams and reservoirs, and atmospheric deposition and other processes also contribute to deliveries (Alexander et al., 2008).

However, demand reductions for US biobased energy feedstocks have potential to mitigate the short-term impacts of population and income growth over the next decade if, as some studies have estimated, repeal would reduce demand by 20% or more. Overall corn-soy production would still rise over time in such a scenario thanks to the US Heartland's general productivity advantage compared to the rest of the world. This could make repeal of RFS2 a meaningful contributor to environmental goals when combined with other changes to management practices and policy interventions (e.g., carbon pricing, restoring depressional wetlands).

Our analysis relies on an aggregated model of corn and soybean production as a composite commodity, meaning that results are limited by the assumption that practices for corn-soy rotations and continuous cropping remain similar in the future. Given the different yields and life cycle greenhouse gas emissions associated with corn and soybeans, other policy changes could differentially impact demand for corn starch-based ethanol, soy-based biodiesel, and their various co-products (Schnitkey et al., 2021; Xu et al., 2022). Future analysis could explore this limitation and alternative policy outcomes by modeling each crop separately. More generally, the SIMPLE-G-US-CS partial-equilibrium model is best suited for projecting changes in scenarios where anything not explicitly introduced as an exogenous shock (in this case, population, income and total factor productivity) is assumed unchanged; in other words, our analysis does not assume or anticipate any other policy changes that would impact corn-soy demand, costs, or production practices, nor global/regional shocks such as pandemics. While our gridded partial-equilibrium framework allows us to account for spatial heterogeneities in various system parameters, it also poses a challenge for rigorous sensitivity and uncertainty analysis given the large number of parameters.

Given its "highly accurate annual measures of crops and cropland areas" (Lark et al., 2021), the choice of the USDA Crop Data Layer is appropriate for approximating spatial patterns of production to apply estimates of spatially-varying parameters (e.g., yield, fertilizer application rates) when combined with other data sets. We note, however, that our analysis is limited to outcomes associated with corn and soybean farming under policy interventions that largely take land out of production for that purpose. Wang et al. (2022) questions the reliability of CDL for studies of land use change, and the SIMPLE-G-US-CS model also does not predict what land taken out of corn-soy production is then used for. As such, a different approach and input data set may be more appropriate if one wishes to make a full accounting of greenhouse gas emissions impacts or other changes associated with land use change.

These limitations notwithstanding, this paper offers a novel analysis of the connections between demand for corn ethanol; future changes to population, income, and productivity; and nitrate leaching outcomes, placed in the context of existing renewable fuel standards and goals for nutrient management in the Mississippi River Basin.

CRediT authorship contribution statement

David R. Johnson: Conceptualization, Methodology, Formal analysis, Visualization, Writing, Funding acquisition. **Nathan B. Geldner:** Methodology, Software, Formal analysis, Writing. **Jing Liu:** Resources, Writing. **Uris Lantz Baldos:** Resources, Writing. **Thomas Hertel:** Conceptualization, Writing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was funded by the US National Science Foundation, award 1855937. The funding organization had no role in any part of this analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2023.113497.

References

Alexander, R.B., Smith, R.A., Schwarz, G.E., Boyer, E.W., Nolan, J.V., Brakebill, J.W., 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. Environ. Sci. Technol. 42, 822–830. https://doi.org/10.1021/es0716103.

Arita, S., Grant, J., Sydow, S., Beckman, J., 2022. Has global agricultural trade been resilient under coronavirus (COVID-19)? Findings from an econometric assessment of 2020. Food Pol. 107, 102204 https://doi.org/10.1016/j.foodpol.2021.102204.

Ator, S.W., Blomquist, J.D., Webber, J.S., Chanat, J.G., 2020. Factors driving nutrient trends in streams of the Chesapeake Bay watershed. J. Environ. Qual. 49, 812–834. https://doi.org/10.1002/jeq2.20101.

Ator, S.W., Denver, J.M., 2015. Understanding Nutrients in the Chesapeake Bay Watershed and Implications for Management and Restoration—The Eastern Shore (No. 1406). U.S. Geological Survey.

Babcock, B.A., 2013. Ethanol without subsidies: an oxymoron or the new reality? Am. J. Agric. Econ. 95, 1317–1324.

Baldos, U.L.C., Haqiqi, I., Hertel, T.W., Horridge, M., Liu, J., 2020. SIMPLE-G: a multiscale framework for integration of economic and biophysical determinants of sustainability. Environ. Model. Software 133, 104805. https://doi.org/10.1016/j.envsoft.2020.104805.

Black, R.E., Allen, L.H., Bhutta, Z.A., Caulfield, L.E., De Onis, M., Ezzati, M., Mathers, C., Rivera, J., Maternal, Group, C.U.S., 2008. Maternal and child undernutrition: global and regional exposures and health consequences. Lancet 371, 243–260.

Brooks, B.W., Lazorchak, J.M., Howard, M.D., Johnson, M.-V.V., Morton, S.L., Perkins, D. A., Reavie, E.D., Scott, G.I., Smith, S.A., Steevens, J.A., 2016. Are harmful algal blooms becoming the greatest inland water quality threat to public health and aquatic ecosystems? Environ. Toxicol. Chem. 35, 6–13.

Busch, J., Ferretti-Gallon, K., 2017. What drives deforestation and what stops it? A meta-analysis. Rev. Environ. Econ. Pol. 11, 3–23. https://doi.org/10.1093/reep/rew013.

Carter, C.A., Rausser, G.C., Smith, A., 2017. Commodity storage and the market effects of biofuel policies. Am. J. Agric. Econ. 99, 1027–1055. https://doi.org/10.1093/ajae/aaw010.

Chen, X., Khanna, M., 2018. Effect of corn ethanol production on Conservation Reserve Program acres in the US. Appl. Energy 225, 124–134.

Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.

Dominguez-Faus, R., Folberth, C., Liu, J., Jaffe, A.M., Alvarez, P.J., 2013. Climate change would increase the water intensity of irrigated corn ethanol. Environ. Sci. Technol. 47, 6030–6037.

Gómez, M.I., Barrett, C.B., Raney, T., Pinstrup-Andersen, P., Meerman, J., Croppenstedt, A., Carisma, B., Thompson, B., 2013. Post-green revolution food systems and the triple burden of malnutrition. Food Pol. 42, 129–138.

Griffith, R., Redding, S., Reenen, J.V., 2004. Mapping the two faces of R&D: productivity growth in a panel of OECD industries. Rev. Econ. Stat. 86, 883–895. https://doi.org/10.1162/0034653043125194.

Haqiqi, I., Bahalou Horeh, M., 2021. Assessment of COVID-19 impacts on U.S. counties using the immediate impact model of local agricultural production (IMLAP). Agric. Syst. 190, 103132 https://doi.org/10.1016/j.agsy.2021.103132.

Hochman, G., Zilberman, D., 2018. Corn ethanol and U.S. Biofuel policy 10 Years later: a quantitative assessment. Am. J. Agric. Econ. 100, 570–584. https://doi.org/10.1093/ajae/aax105.

International Energy Agency, 2020. World energy Outlook – topics [WWW Document]. IEA WEO. URL. https://www.iea.org/topics/world-energy-outlook, 4. JanuaryMarch.22.

Jeswani, H.K., Chilvers, A., Azapagic, A., 2020. Environmental sustainability of biofuels: a review. Proceed. Royal Soc. A 476, 20200351.

Kocak, E., Bilgili, F., Bulut, U., Kuskaya, S., 2022. Is ethanol production responsible for the increase in corn prices? Renew. Energy 199, 689–696.
Kucharik, C.J., 2003. Evaluation of a process-based agro-ecosystem model (Agro-IBIS) across the US corn belt: simulations of the interannual variability in maize yield. Earth Interact. 7.
Lark, T.J., Hendricks, N.P., Smith, A., Pates, N., Spawn-Lee, S.A., Bougie, M., Booth, E., Kucharik, C.J., Gibbs, H.K., 2022a. Reply to Taheripour et al. Comments on "Environmental Outcomes of the US Renewable Fuel Standard.
Lark, T.J., Hendricks, N.P., Smith, A., Pates, N., Spawn-Lee, S.A., Bougie, M., Booth, E.G., Kucharik, C.J., Gibbs, H.K., 2022b. Environmental outcomes of the US renewable fuel standard. Proc. Natl. Acad. Sci. USA 119, e2101084119.
Lark, T.J., Hendricks, N.P., Smith, A., Pates, N., Spawn-Lee, S.A., Bougie, M., Booth, E.G., Kucharik, C.J., Gibbs, H.K., 2022c. Environmental outcomes of the US renewable fuel standard. Proc. Natl. Acad. Sci. USA 119, e2101084119. https://doi.org/10.1073/pnas.2101084119.
Lark, T.J., Salmon, J.M., Gibbs, H.K., 2015. Cropland expansion outpaces agricultural and biofuel policies in the United States. Environ. Res. Lett. 10, 044003 https://doi.org/10.1088/1748-9326/10/4/044003.
Lark, T.J., Schelly, I.H., Gibbs, H.K., 2021. Accuracy, bias, and improvements in mapping crops and cropland across the United States using the USDA cropland data layer. Rem. Sens. 13, 968. https://doi.org/10.3390/rs13050968.
Liu, J., Bowling, L., Kucharik, C., Jame, S., Baldos, U., Jarvis, L., Ramankutty, N., Hertel, T., 2022. Multi-scale Analysis of Nitrogen Loss Mitigation in the US Corn Belt. https://doi.org/10.48550/arXiv.2206.07596.
Liu, J., Hertel, T., Bowling, L., Jame, S., Kucharik, C., Ramankutty, N., 2018. Evaluating Alternative Options for Managing Nitrogen Losses from Corn Production. Purdue Policy Research Institute (PPRI) Policy Briefs 4.
Ludena, C.E., Hertel, T.W., Preckel, P.V., Foster, K., Nin, A., 2007. Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts. Agric. Econ. 37, 1–17. https://doi.org/10.1111/j.1574-0862.2007.00218.x.
Mooney, R.J., Stanley, E.H., Rosenthal, W.C., Esselman, P.C., Kendall, A.D., McIntyre, P. B., 2020. Outsized nutrient contributions from small tributaries to a Great Lake. Proc. Natl. Acad. Sci. USA 117, 28175–28182. https://doi.org/10.1073/pnas.2001376117.
Moschini, G., Lapan, H., Kim, H., 2017. The renewable fuel standard in competitive equilibrium: market and welfare effects. Am. J. Agric. Econ. 99, 1117–1142. https://doi.org/10.1093/ajae/aax041.
National Conference of State Legislatures, 2021. State Renewable Portfolio Standards and Goals.
O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122, 387–400.
Perez-Escamilla, R., Bermudez, O., Buccini, G.S., Kumanyika, S., Lutter, C.K., Monsivais, P., Victora, C., 2018. Nutrition disparities and the global burden of malnutrition. BMJ 361, k2252. https://doi.org/10.1136/bmj.k2252.
Rabalais, N.N., Turner, R.E., 2019. Gulf of Mexico hypoxia: past, present, and future. Limnol. Oceanogr. Bull. 28, 117–124.
Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ. Change 42, 153–168.
Sacks, W.J., Kucharik, C.J., 2011. Crop management and phenology trends in the US Corn Belt: impacts on yields, evapotranspiration and energy balance. Agric. For. Meteorol. 151, 882–894.
Sanchez, D.L., Johnson, N., McCoy, S.T., Turner, P.A., Mach, K.J., 2018. Near-term deployment of carbon capture and sequestration from biorefineries in the United States. Proc. Natl. Acad. Sci. USA 115, 4875–4880.
Schnitkey, G., Zulauf, C., Swanson, K., Paulson, N., 2021. 2022 planting decisions, nitrogen fertilizer prices, and corn and soybean prices. farmdoc daily 11.
Scully, M.J., Norris, G.A., Falconi, T.M.A., MacIntosh, D.L., 2021. Carbon intensity of corn ethanol in the United States: state of the science. Environ. Res. Lett. 16, 043001.
Seppelt, R., Beckmann, M., Ceauşu, S., Cord, A.F., Gerstner, K., Gurevitch, J., Kambach, S., Klotz, S., Mendenhall, C., Phillips, H.R., 2016. Harmonizing biodiversity conservation and productivity in the context of increasing demands on landscapes. Bioscience 66, 890–896.
Shah, T., Burke, J., Vullholth, K., Angelica, M., Custodio, E., Daibes, F., Van Dijk, J.H., Giordano, M., Girman, J., Van Der Gun, J., 2007. Groundwater: a global assessment of scale and significance. In: Water for Food Water for Life: A Comprehensive Assessment of Water Management in Agriculture, pp. 395–423. Earthscan.
Smith, D.R., King, K.W., Williams, M.R., 2015. What is causing the harmful algal blooms in Lake Erie? J. Soil Water Conserv. 70, 27A–29A. https://doi.org/10.2489/jswc.70.2.27A.
Spawn-Lee, S.A., Lark, T.J., Gibbs, H.K., Houghton, R.A., Kucharik, C.J., Malins, C., Pelton, R.E., Robertson, G.P., 2021. Comment on 'Carbon intensity of corn ethanol in the United States: state of the science. Environ. Res. Lett. 16, 118001.
Sun, S., Ordonez, B.V., Webster, M.D., Liu, J., Kucharik, C.J., Hertel, T., 2020. Fine-Scale analysis of the energy–land–water nexus: nitrate leaching implications of biomass cofiring in the midwestern United States. Environ. Sci. Technol. 54, 2122–2132. https://doi.org/10.1021/acs.est.9b07458.
Taheripour, F., Mueller, S., Kwon, H., Khanna, M., Emery, I., Copenhaver, K., Wang, M., CropGrower, L.L.C., 2022. Comments on "Environmental Outcomes of the US Renewable Fuel Standard.
US Environmental Protection Agency, 2022. Renewable Fuel Standard (RFS) Program: RFS Annual Rules.
US EPA, O., 2022a. EPA issues emergency fuel waiver for E15 sales [WWW Document]. URL. https://www.epa.gov/newsreleases/epa-issues-emergency-fuel-waiver-e15-sales. June.27.22.
US EPA, O., 2022b. EPA takes action to reset and strengthen the RFS Program [WWW Document]. URL. https://www.epa.gov/newsreleases/epa-takes-action-reset-and-strengthen-rfs-program. June.27.22.
Us Epa, O., 2016. States Develop New Strategies to Reduce Nutrient Levels in Mississippi River, Gulf of Mexico [WWW Document]. US EPA. URL. https://www.epa.gov/newsreleases/states-develop-new-strategies-reduce-nutrient-levels-mississippi-river-gulf-mexico, 4.December.22.
US Federal Register, 2007. Energy Independence and Security Act of 2007.
US Federal Register, 2005. Energy Policy Act of 2005.
USDA ERS, 2021. International Agricultural Productivity [WWW Document]. URL. https://www.ers.usda.gov/data-products/international-agricultural-productivity/.
USDA ERS - Feedgrains Sector at a Glance [WWW Document], n.d. URL https://www.ers.usda.gov/topics/crops/corn-and-other-feedgrains/feedgrains-sector-at-a-glance/ (accessed 4.JanuaryMay.22).
VanLoocke, A., Twine, T.E., Kucharik, C.J., Bernacchi, C.J., 2017. Assessing the potential to decrease the Gulf of Mexico hypoxic zone with Midwest US perennial cellulosic feedstock production. Gcb Bioenergy 9, 858–875.
Wang, M., Wander, M., Mueller, S., Martin, N., Dunn, J.B., 2022. Evaluation of survey and remote sensing data products used to estimate land use change in the United States: evolving issues and emerging opportunities. Environ. Sci. Pol. 129, 68–78. https://doi.org/10.1016/j.envsci.2021.12.021.
Watson, S.B., Miller, C., Arhonditsis, G., Boyer, G.L., Carmichael, W., Charlton, M.N., Confesor, R., Depew, D.C., Höök, T.O., Ludsin, S.A., Matisoff, G., McElmurry, S.P., Murray, M.W., Peter Richards, R., Rao, Y.R., Steffen, M.M., Wilhelm, S.W., 2016. The re-eutrophication of Lake Erie: harmful algal blooms and hypoxia. Harmful Algae 56, 44–66. https://doi.org/10.1016/j.hal.2016.04.010.
Xu, H., Ou, L., Li, Y., Hawkins, T.R., Wang, M., 2022. Life cycle greenhouse gas emissions of biodiesel and renewable diesel production in the United States. Environ. Sci. Technol. 56, 7512–7521. https://doi.org/10.1021/acs.est.2c00289.