IMPACTS OF THE RENEWABLE FUEL STANDARD ON AMERICA'S LAND AND WATER RESOURCES

Summary of research presented at the American Academy for the Advancement of Science (AAAS) Annual Meeting, February 15, 2019, in Washington, D.C.[†]

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SUMMARY

The U.S. Renewable Fuel Standard (RFS) has been implicated in changes to agricultural commodity markets[1,2], shifts to crop rotation sequences[3,4], and the conversion of natural land to crop production[5,6]. However, direct attribution of these effects and their environmental consequences to the RFS has remained elusive and uncertain[7]. To address this knowledge gap, we analyzed the effects of the RFS on corn, soybean, and wheat prices and linked the results to econometric models of land use response and spatially explicit observations of land use change to better understand the extent to which the RFS contributed to changes on the landscape. We then incorporated these changes into biophysical[8,9] and empirical models[10,11] to assess their effects on water quality, consumptive crop water use, and greenhouse gas emissions.

Our findings suggest that in the eight years following expansion of the RFS in 2007, the policy bolstered the amount of corn planted on existing cropland each year by an average of 6.9 million acres, or 8.2% more than would have occurred without the RFS. During the same time span, the RFS also stimulated an increase in total cropland area of 2.8 million acres, which accounts for 43% of the total cropland area change observed during the period. These changes have wide ranging environmental impacts. For example, intensified corn production on existing cropland contributed to an estimated 319,000 metric tons yr^{-1} of additional nitrogen applications and associated nitrous oxide emissions of 3.1 MMT CO_2e yr^{-1} (million metric tons of carbon dioxide equivalents per year). In addition, the RFS-related changes to cropland extent committed carbon emissions of 27.1 MMT CO_2e yr^{-1} from land use change and increased annual consumptive water use by 16.7 billion gal yr^{-1}. Combined, the changes to crop rotations and cropland area increased total nitrate leaching by 96,953 metric tons N yr^{-1}, increased edge-of-field phosphorus run-off by 426,354 kg yr^{-1}, and generated edge-of-field soil sediment erosion of 572,190 metric tons yr^{-1}.

This compilation of research provides the first observation-based, spatially explicit accounting of key field-level impacts of the RFS on U.S. land use change and associated environmental outcomes. Our approach provides a blueprint for the integration of comprehensive land change data with causal economic models to measure environmental outcomes across an entire agricultural industry—from the policymaking process through to implementation on the landscape.

[†]For presentation details, see the conference program. This research was supported in part by a grant from the National Wildlife Federation.

BACKGROUND

The RFS is the primary federal policy that guides the production and use of biofuels in the United States. First passed in 2005, the program was greatly expanded as part of the Energy Independence and Security Act of 2007 with the goals of increasing renewable fuel production while reducing greenhouse gas (GHG) emissions and dependence on foreign oil[12]. Given its ambitious scope, the expanded RFS program (commonly known as the RFS2) was predicted to have wide-ranging effects on farm commodity markets, agricultural land use change, and natural resources[13–16]. However, the magnitude of impacts that can be directly attributed to RFS2 implementation has remained highly uncertain, due in part to both the need for time to pass to observe outcomes and the difficulty of establishing a causal chain between the policy and its impacts on the landscape[7].

Potential environmental effects of the RFS2 are expected to stem largely from heightened demand for biofuel feedstocks and associated changes in land use and management needed to produce the crops to meet this demand[17,18]. Increases in feedstock production can be achieved via two different pathways: (i) intensification, or increasing production from existing croplands, and (ii) extensification, or increasing total cropland area. Intensification comprises many potential management shifts including changes to plant breeding and genetics, agronomic inputs, and/or crop rotation sequences. Here, we modeled the recent intensification of corn production on existing cropland as manifested through changes in the frequency of planting corn compared to other crops as well as the associated change in fertilizer inputs. We also estimated the impacts of the RFS2 on extensification by quantifying the contribution of the policy to recently observed cropland expansion and abandonment. We then used a suite of models to assess the impacts of the observed land use changes on various environmental outcomes, including nitrous oxide emissions, carbon emissions, and consumptive crop water use. Together, this work estimates the major land use and management changes associated with the RFS2 and provides insights into select environmental impacts on both existing and newly converted croplands.

PRELIMINARY FINDINGS

Expansion of the RFS increased the prices of commodity crops

We estimate the effects of the RFS2 relative to a counterfactual business as usual (BAU) in which ethanol production satisfies only the volume required by the initial 2005 renewable fuel standard, equivalent to the amount needed to meet standards for reformulated gasoline under the 1990 Clean Air Act. Relative to BAU, the RFS2 required 5.5 billion gallons of additional ethanol, which removed about 1.3 billion bushels of corn from the food system after accounting for by-products that can be fed to animals[1].

This expansion of the RFS program increased the price of corn in the U.S. by approximately 31% [80% Confidence Interval (CI): 14%, 58%] compared to the BAU without the RFS2 (**Fig. 1**). The increased demand for biofuel production also had spillover effects on other crops, increasing the price of soybeans by 19% [CI: 2%, 55%] and wheat by 20% [CI: 9%, 49%]. These persistent increases represent the average effects of the RFS2 between 2006 and 2010, though the magnitude varies annually, and long-run effects are estimated as a 30% increase in the price of corn and a 20% increase in the prices of other crops[19].

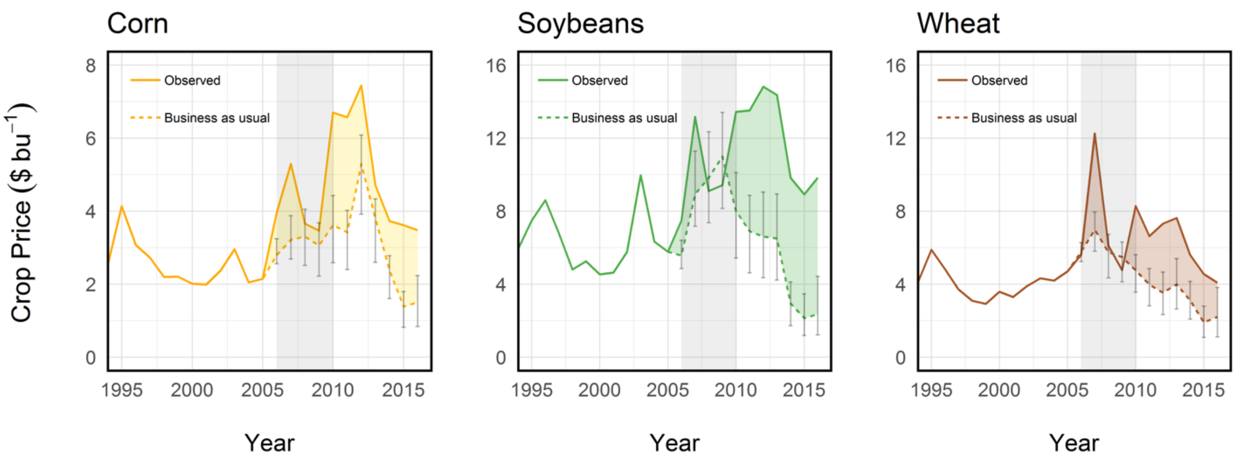

Figure 1: Observed and business-as-usual (BAU) estimates for the prices of corn, soybeans, and wheat. Vertical bars represent the 80% confidence intervals for each BAU spot price. Each year denotes a crop year, e.g., 2006 is Sep 2006 through Aug 2007 for corn and soybeans and June 2006 through May 2007 for wheat. Averages for 2006-2010 (highlighted in grey) were used to derive the estimates reported in the text, though long-run persistent impacts were consistent with these results[1,19].

Higher corn prices increased the frequency of planting corn on existing cropland

The upturn in the price of corn relative to other crops increased the likelihood of producers planting corn on existing cropland. We estimate that the RFS2 increased the annual area planted to corn on existing cropland by an average of 6.9 million acres[‡], or about 8.2% more than the extent expected without the RFS2. The increase in corn area was largest in the Dakotas, Northwest Minnesota, and Mississippi Delta regions, where 30-50% of the current corn area can be attributed to the expansion of the RFS[20].

This proliferation of corn occurred through changes in the rotation patterns of corn relative to other crops. For example, the probability of continuous corn rotations (CC; corn planted immediately after corn) increased 2.4 percentage points due to RFS2 prices compared to the BAU, with the greatest influence in the Upper Midwest (**Figs. 2a-b**). To accommodate this increase in corn monoculture, the average probability of other, non-corn crops being planted in back-to-back years decreased by 4.0 percentage points (**Figs. 2c-d**). In contrast to these relatively universal changes in continuous crop patterns across the U.S., changes in the probability of corn being planted in equal rotation with other crops varied by region (**Figs. 2e-f**). In core agricultural locations where rotating corn with other crops was already common (e.g., Iowa), there was a reduction in corn-other (CO) rotations associated with the shifting trend towards increased continuous corn production. On the other hand, where corn was less common—areas like North Dakota, South Dakota, and the Mississippi Alluvial Plain—more corn was added into rotations previously dominated by other crops like soybeans and wheat. In total across the study region, corn-other rotations increased by 1.6 percentage points overall.

[‡]Note that our model of key growing regions accounts for 91.6% of corn acres in the U.S. If one assumes a similar response in the remaining unmodeled area, then the nationwide change in corn area is 7.5 M acres, or 8.9% more than the extent expected without the RFS2.

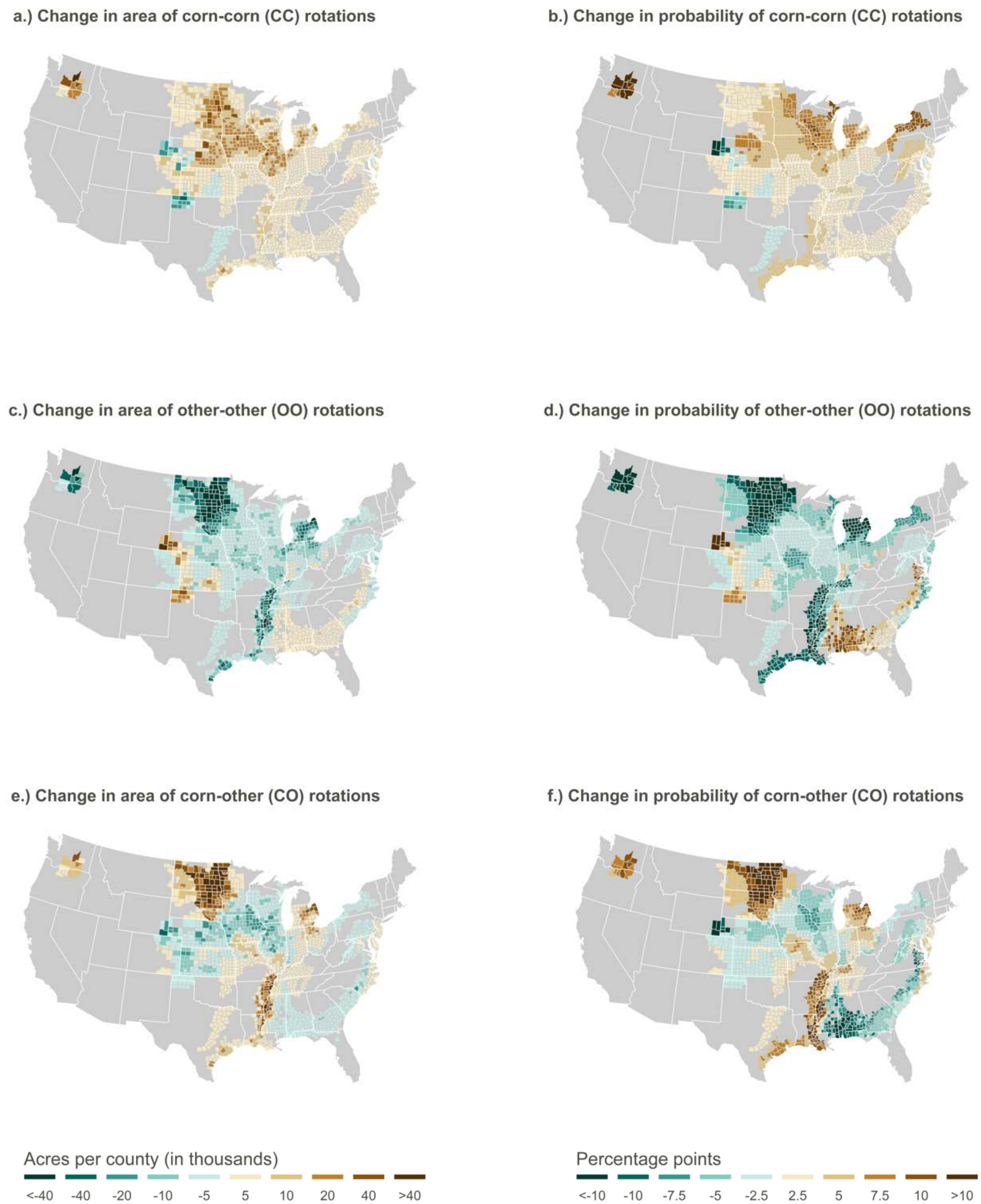

Figure 2: Changes in both absolute area (left column) and probability (right column) of continuous corn (CC), continuous other crops (OO), and corn-other crop rotations (CO) in the RFS2 scenario relative to business as usual.

Additional fertilizer use and nitrous oxide emissions on existing croplands

The increased frequency of corn planted on existing cropland led to greater application of nitrogen (N) on the landscape to grow crops. We estimate an additional 319,000 metric tons of N from synthetic fertilizer was applied to existing croplands on average each year between 2008 and 2016 (**Fig. 3**). A portion of the N fertilizer applied to croplands is often emitted to the atmosphere as the greenhouse gas nitrous oxide (N_2O). We estimate that the additional N application due to changes in crop rotations associated with the RFS2 led to additional N_2O emissions of 3.1 MMT CO_2e yr^{-1} (million metric tons in CO_2 equivalents) compared to a non-RFS2 scenario. This represents roughly a 2-6% increase over existing N_2O emissions from all cropland[21,22].

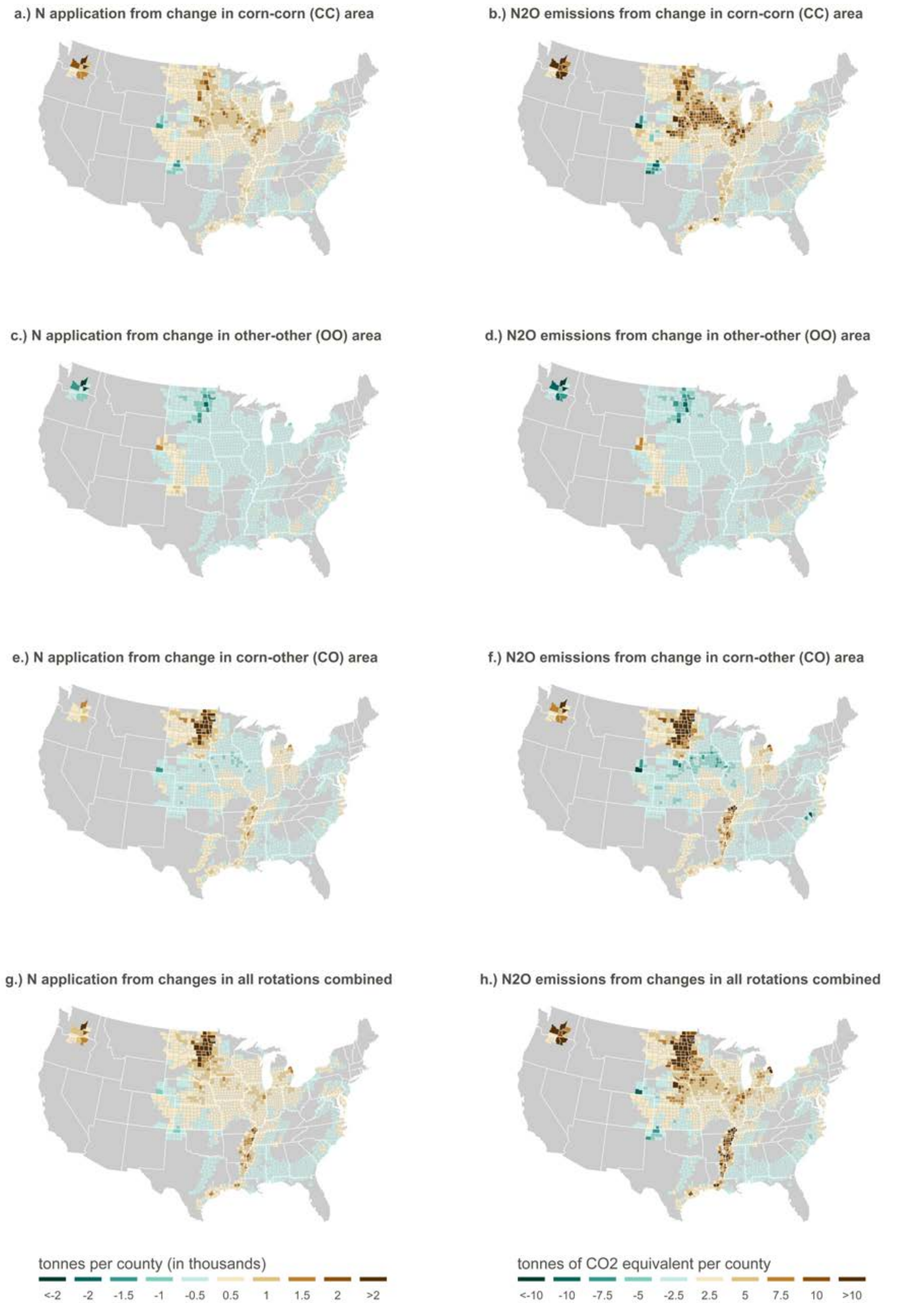

Figure 3: Changes in nitrogen (N) fertilizer application (left column) and associated nitrous oxide (N_2O emissions (right column) as a result of changes in area of continuous corn (CC), continuous other crops (OO),

and corn-other crop rotations (CO) due to the RFS2. The bottom row represents total N and N_2O impacts from all three rotation changes combined.

Water quality impacts of increased corn production

Increasing the frequency of planting corn on existing cropland and the related changes in management are often associated with heightened risks for degradation of groundwater and surface water quality[3,8,23]. We estimate that changes in crop rotations due to the RFS2 led to additional annual leaching of 67,618 metric tons of nitrogen as nitrate (**Fig. 4**). This loss of nitrate to the environment represents vertical seepage below the root zone, where nutrients are no longer accessible for crop utilization and instead may contribute to contamination of groundwater and drinking wells. The high nitrate leaching values are primarily driven by the larger amount of nitrogen fertilizer inputs for corn relative to other crops as well as greater mineralization of organic nitrogen that is also prone to leaching.

The changes in crop rotations due to the RFS2 also affected outcomes relevant to surface water quality. We estimate that total edge-of-field phosphorus (P) run-off increased by 144,478 kg P each year under the RFS2 (**Fig. 5**). This increase is primarily driven by the higher P fertilizer requirements of corn as well as increased soil erosion, which transports additional P-laden sediment downstream. When this P enters waterways it contributes to the process of eutrophication and can lead to both hypoxia and harmful algal blooms[3,8,23].

The greater cultivation of corn and reduction of other crops also amplified soil erosion on existing croplands. In total, we estimate that the RFS2 caused an additional 152,148 metric tons of edge-of-field soil sediment erosion. These losses of soil from crop fields can degrade soil quality over time and in waterways contribute to both sedimentation and impairment of water clarity.

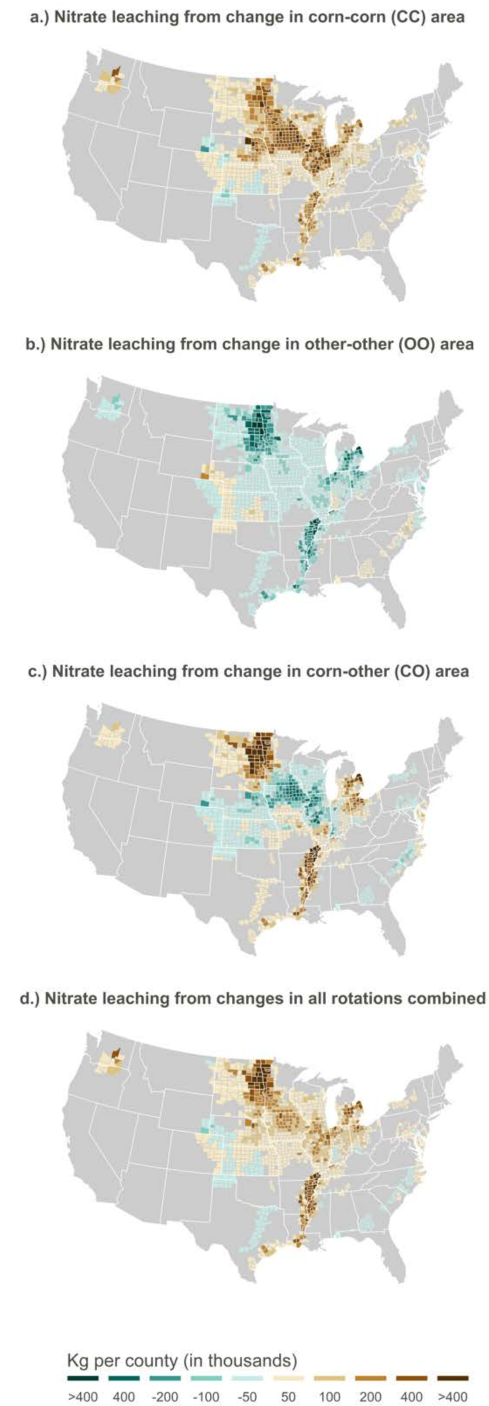

Figure 4: Nitrate (NO_3) leaching due to changes in crop rotations associated with the RFS2.

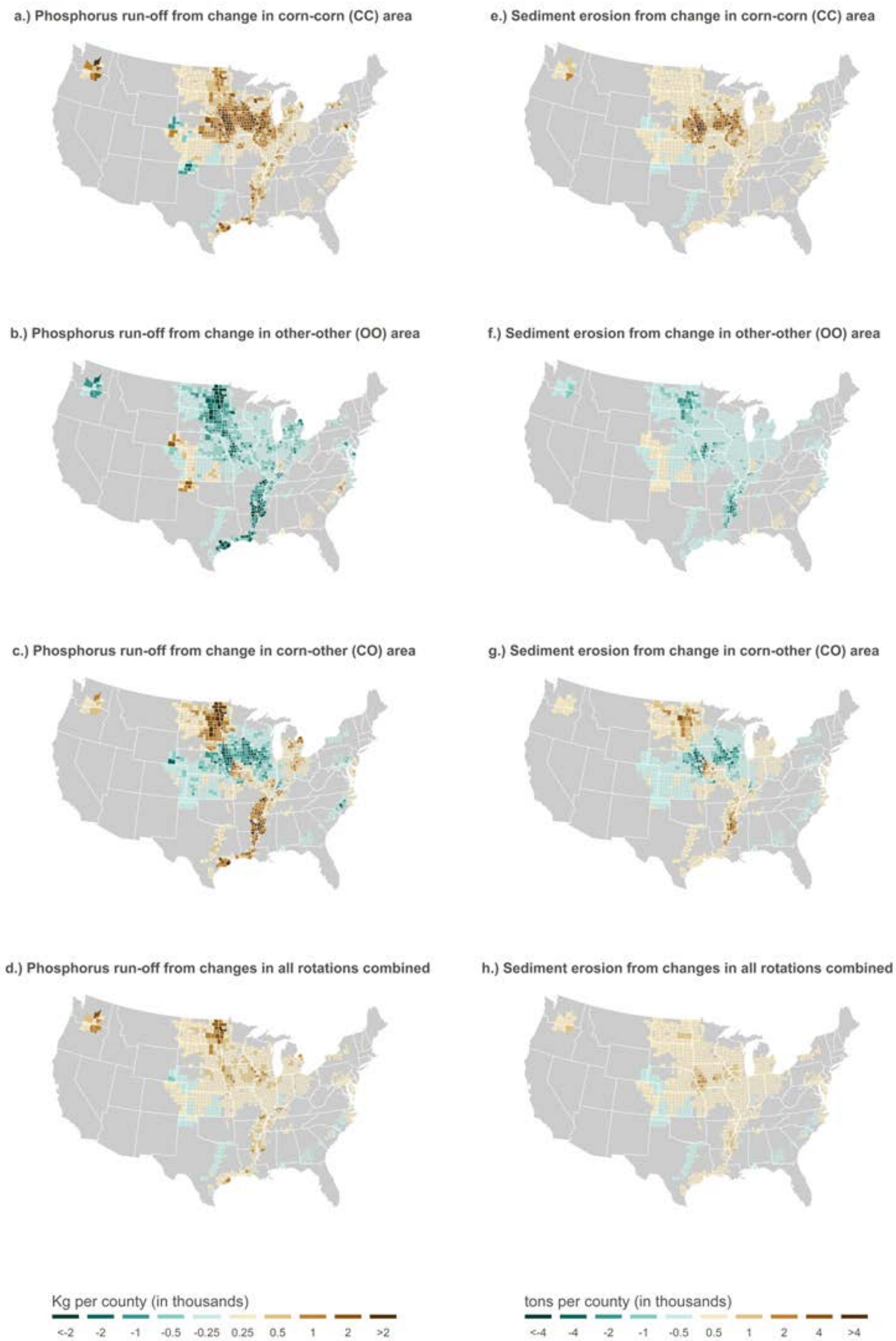

Figure 5: Edge-of-field phosphorus run-off and sediment erosion from changes in crop rotations associated with the RFS2.

Higher crop prices also increased total cropland area

Increased crop prices also increased the likelihood that previously uncultivated natural and semi-natural areas were converted to cropland. We estimate that the RFS2 caused an additional 1.6 million acres of cropland expansion in the period 2008-2016—roughly 15% of the total expansion observed during the period and 19% greater than what would have occurred without the policy. In addition, higher prices for crops reduced rates of cropland abandonment. This means that less cropland returned to grass or natural cover—either through transition to pasture or enrollment into the Conservation Reserve Program. We estimate that the RFS2 decreased abandonment by 35% compared to the BAU, resulting in 1.2 million acres of cropland remaining in production instead of transitioning to noncropland. The net result of these extensive changes was an increase in actively cropped area of 2.8 million acres relative to the BAU. This increase due to the RFS2 equals 43% of the total observed increase in cropland area during the study period[24], suggesting the change in cropland area was 76% larger than it would have been in the absence of the policy.

Cropland expansion and reduced abandonment increased carbon emissions and water use

Cropland extensification can cause substantial emissions of carbon by degrading ecosystem carbon stocks embodied in plants and soils. We estimate that total committed carbon emissions from cropland expansion associated with the RFS2 from 2008 to 2016 were 116 MMT CO_2e, or approximately 15 MMT CO_2e yr^{-1} (**Fig. 6**). At the same time, foregone sequestration due to reduced rates of cropland abandonment because of the RFS2 was 103 MMT CO_2e assuming the land would have been enrolled in the CRP and sequestering carbon for 15 years. Together, the change in cropland area due to the RFS2 caused a total net flux of 219 MMT CO_2e (95% CI: 205 - 239 MMT CO_2e) to the atmosphere, or 27.1 MMT CO_2e yr^{-1}. These land use change emissions are in addition to any management-related emissions associated with the increased agricultural activity on the additional cropland extent.

Crops grown on new croplands due to the RFS2 used 10.5 billion gallons more water per year than the grasslands and natural vegetation they replaced. Similarly, crops that grew on cropland which otherwise would have been abandoned in absence of the RFS2 consumed over 6.2 billion more gallons of water annually than the grasslands with which they would have been replaced. These estimates of consumptive crop water use or evapotranspiration (ET) include water supplied through any source (e.g. groundwater, surface water, or precipitation) in both irrigated and rainfed systems.

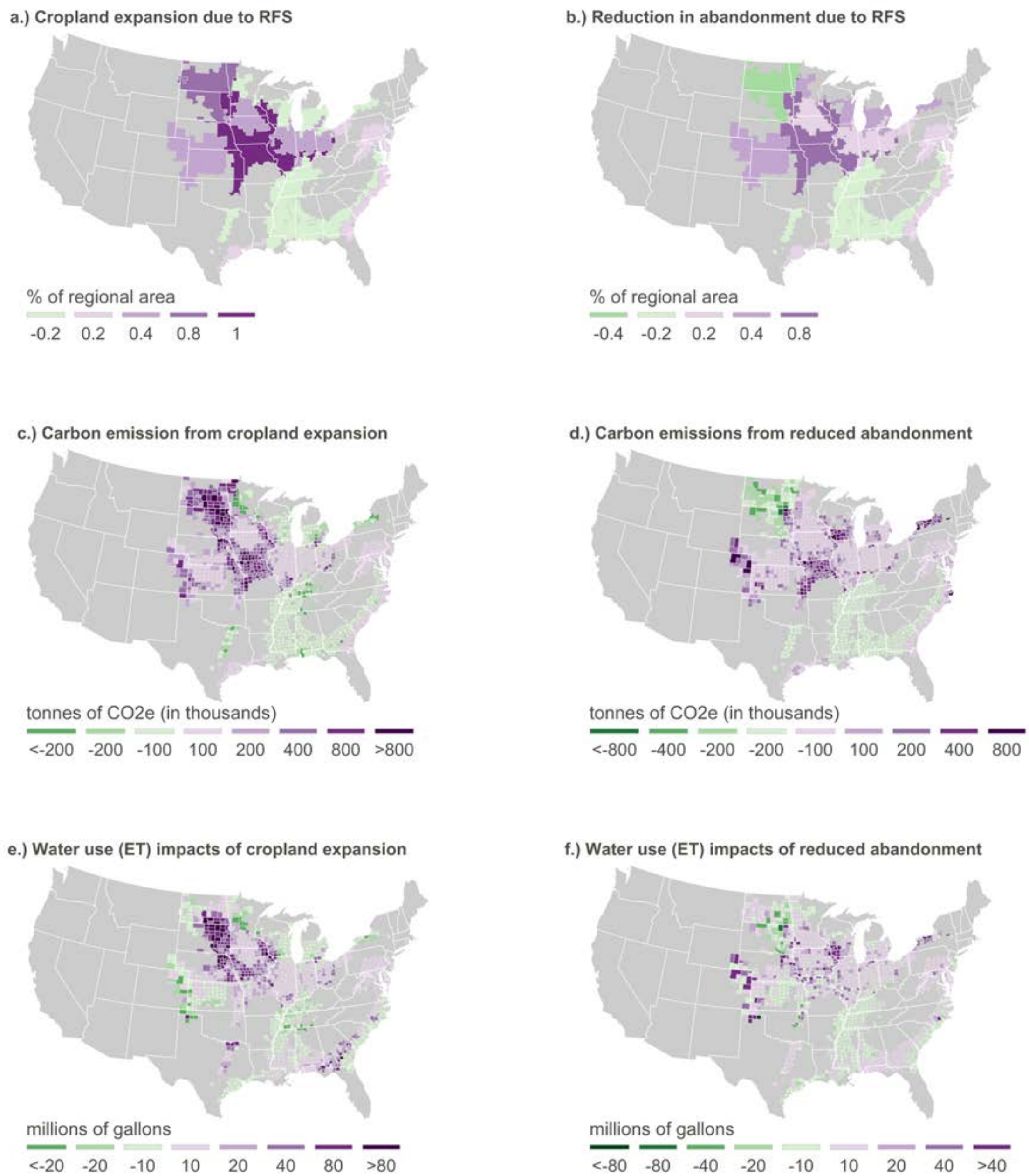

Figure 6: Change in cropland area, carbon emissions, and crop consumptive water use due to the expansion of cropland and reduction in abandonment associated with the RFS2.

Additional nitrogen, phosphorus, and sediment impacts of RFS2-induced cropland area change

Increased cropland expansion due to the RFS2 and the perpetuation of existing croplands that would have been abandoned in the absence of the policy both contributed to additional nitrogen, phosphorus, and soil loss impacts to water quality. We estimate that the combined output of cropland area changes led to increases in nitrate leaching of 29,335 metric tons of N yr^{-1}, increases in phosphorus run-off of 278,876 kg P yr^{-1}, and increases in sediment yield of 420,042 metric tons yr^{-1} (**Fig. 7**). These water quality outputs from cropland area changes are in addition to those generated from the changes in crop rotations on existing cropland due to the RFS2 and reflect the ongoing, elevated impacts of croplands on water quality relative to uncultivated areas.

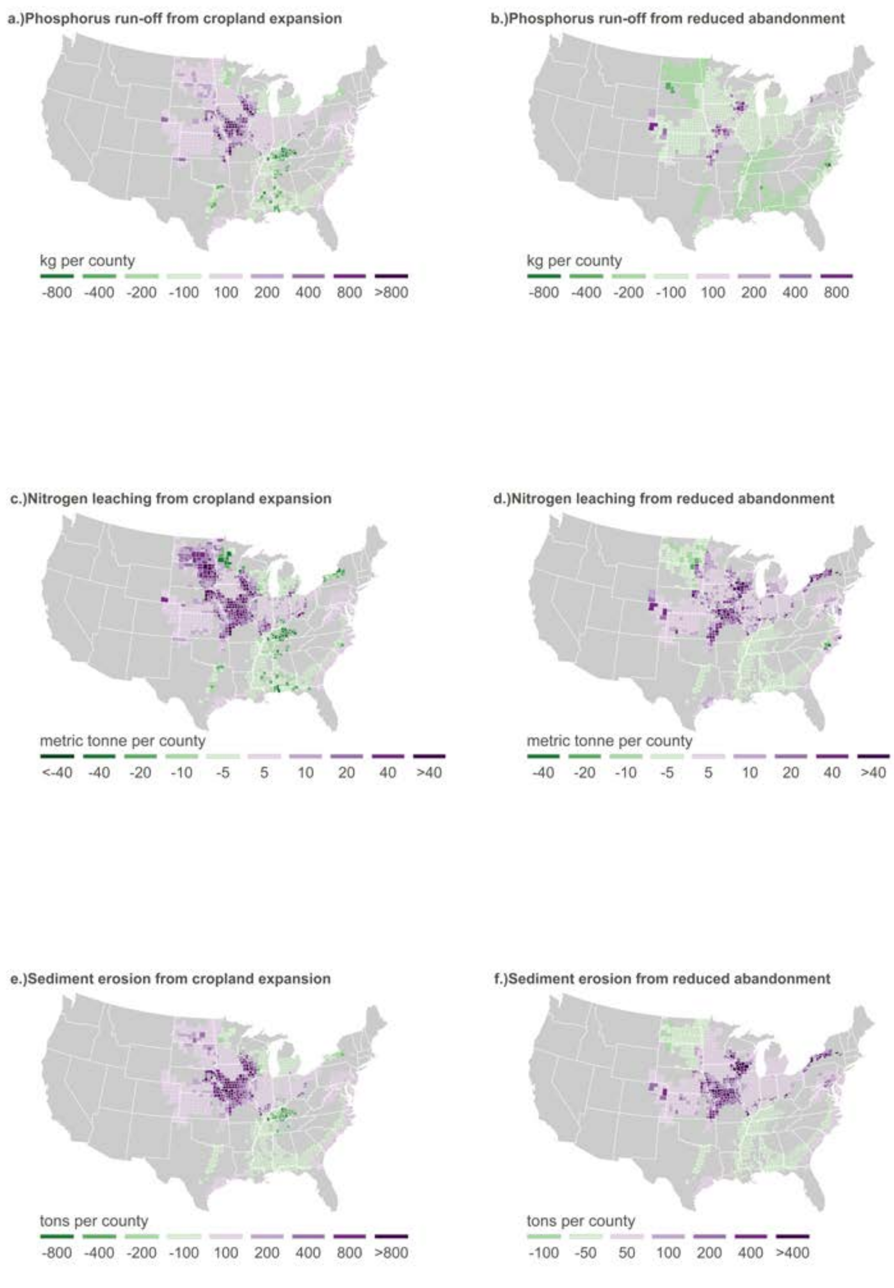

Figure 7: Changes in phosphorus run-off, nitrogen leaching, and sediment erosion due to the expansion of cropland and reduction in abandonment associated with the RFS2.

METHODS

Price Impacts

We assessed the impact of the RFS2 on U.S. corn, soybean, and wheat prices by comparing observed market prices to a counterfactual business as usual (BAU) scenario without the RFS2, where BAU ethanol production satisfies only the volume required by the 2005 renewable fuel standard, equivalent to the amount needed to meet standards for reformulated gasoline under the 1990 Clean Air Act. Our analysis therefore estimates the additionality effects of the 2007 expansion of the RFS program above what would have otherwise likely occurred to meet demand for ethanol as an oxygenate.

The RFS2 also requires increased biodiesel use. However, we do not incorporate the effect of biodiesel on soybean prices because the effect is likely very small. By weight, about 80% of each bean becomes meal and the other 20% becomes oil. Thus, even though 30% of soybean oil was used to make biodiesel in 2017, less than 3% of soybeans ended up in biodiesel[19].

Our approach closely follows that of Carter, Rausser, and Smith (2017) to account for competing shocks in demand due to changes in inventory, weather, and external markets[1], and extends the work to estimate the impacts of the RFS2 on soybean and wheat prices. In particular, the vector autoregressive model of Carter, Rausser, and Smith incorporates the fact that the expanded RFS was a persistent rather than a transitory shock to agricultural markets. This distinction is important because persistent shocks have larger price effects than transitory shocks. The market can respond to a transitory shock, such as poor growing season weather, by drawing down inventory. This action mitigates the price effect. A persistent shock, such as an increase in current and expected future demand, cannot be mitigated by drawing down inventory. To identify these two types of shocks, the model used data on inventory levels and on the term structure of futures prices. See Smith (2018) for details[19].

Effects on crop rotations

Based on an estimated 30% persistent increase in the price of corn and 20% increase in the prices of soybeans and wheat, we independently modeled the effects of crop price changes on crop rotations and rates of conversion of land to and from cropland. To model crop rotational changes we followed the approach of Hendricks et al. 2014 to estimate how changes in prices impact the probabilities of continuous corn, continuous other crops, and corn-other crop rotations[3,25]. To estimate the model, we built a spatiotemporal database using field boundary data from the 2008 USDA Common Land Unit[26,27] supplemented by satellite-extracted field boundaries[28], and associated information on annual crop type, soil properties, and climate from the Cropland Data Layer[29], the Soil Survey Database (SSURGO)[30], and the PRISM climate group[31], respectively. Crop futures and basis prices were obtained from the Bloomberg Terminal[32]. We calculated the marginal rotational probabilities for all fields greater than 15 acres that were in regions where (i) greater than 20% of the total area was cropland, (ii) more than 10% of cropland acreage was planted to corn, and (iii) greater than 50% of the cropland not planted to corn was planted to a crop for which prices were available (specifically wheat, soybeans, rice, and cotton). This set of criteria ensured adequate data was available to train the model. Our final sample included 3.6 million fields that accounted for 91.6% of corn acreage. We then derived the change in probability due to the RFS2 for each of these crop fields.

Cropland area changes

To assess land use changes at the extensive margin, we estimated the probability of transitioning between cropland and pasture or transitioning between cropland and CRP as a function of cropland, pasture, and CRP returns. The model uses point-level land use transition data based on observed annual land use transitions in the National Resources Inventory (NRI) from 2000 to 2012. We then used the model to predict the change in transitions between 2008 and 2016 based on changes in prices[33]. During this period, we predicted changes for eight years, with the first transitions occurring between the 2008 growing season and the 2009 growing season. This approach may thus underestimate the total extensive land response to the RFS2, as some land likely came into production prior to the 2009 growing season and after the 2016 growing season. In order to allow for geographic variation in the extensive response of land use to crop prices, we trained independent models for each of 7 different Land Resource Regions (LRR) corresponding to aggregated Major Land Resource Areas (MLRAs) from the Natural Resources Conservation Service. For a full description of the model, see Hendricks (2018)[34].

We then mapped observed land use change at the field level during our study period following Lark et al. (2015) and using updated recommended practices[35] to extend the analysis to 2008-2016[24]. These data were used to link the estimated extent of land use change associated with the RFS2 in each major LRR region to specific locations of observed conversion for the purpose of enumerating environmental impacts. Thus, while this high-resolution data was used to identify the possible locations and characteristics of converted land, the data from the NRI was used to estimate the magnitude of this conversion that occurred within each county and region and which could be attributed to the RFS2. This mixed data approach thereby combined the USDA NRI data's high certainty and long-term temporal coverage (prior to any RFS2 price signals) with the field-level specificity of the satellite-based land conversion observed during the study period[35].

N application and N_2O emissions

Rates of N fertilizer application were developed using county-level estimates of fertilizer and manure N compiled by the U.S. Geological Survey[36,37], county-level estimates of area planted to specific crops (corn, soybean, and wheat) from the Census of Agriculture[38], and typical fertilizer N application ratios for the three crop types (corn, soybeans, wheat) from university extension publications[39]. By assuming that the typical N application ratios were present across all counties, we derived the county-specific N application rates for each crop type given the total N applied across the county and the area devoted to each crop. We used and report mean values for 2007-2016 in order to encompass both the study time period and two years of Census data. We then modeled the change in N_2O emissions from fertilizer applications associated with the changes in crop rotations by applying the nonlinear nitrogen effect model (NL-N-RR) of Gerber et al. (2016)[10] to the N application maps described above. N_2O emission estimates were converted to CO_2e by assuming a 100-year global warming potential of 265[40].

Carbon emissions

We used the methods of Spawn et al. (2019) to estimate the carbon emissions associated with RFS2-related land use change[11]. Carbon emissions from soil and biomass degradation associated with land use change were modeled for all observed conversion to cropland. In addition, a variant of the Spawn et al. model was created to assess forgone sequestration associated with reduced rates of abandonment. This model was structurally the same as that used for conversion to cropland but used a carbon response function[41] for conversion of cropland to grassland to estimate expected soil organic carbon accumulation over a 15 year period – the average length of a CRP contract. We thus assumed that any abandoned land would have been retired to the CRP and sequestered carbon for the duration of its contract. To attribute emissions to the RFS2, we multiplied total emissions from all observed land use change within a given LRR by the percentage of that region's observed land use change that could be attributed to the RFS2, as described above.

Water use

We used the process-based biophysical model Agro-IBIS[9] to simulate patches of land that were classified as undergoing conversion to cropland or abandonment from cropland[24]. Model inputs included daily weather from gridMET[42], soil texture from POLARIS[43], slope from the U.S. Geological Survey[44], and irrigation extent from the Moderate Resolution Imaging Spectroradiometer (MODIS) Irrigated Agriculture Dataset for the

United States (MIrAD-US)[45]. Irrigation water was applied to irrigated crops on a daily basis if the available water content was less than half of the maximum available water content (soil texture-dependent). Daily irrigation amount was the minimum of 150 mm and the difference between maximum and actual available water content. Consumptive water use was calculated in the model as mean annual evapotranspiration for 2007-2016 and represents water used by crops supplied through both precipitation and irrigation.

Water quality

We used Agro-IBIS[9] to simulate the water quality impacts of changes to both crop rotations and total cropland area (see additional details in previous section). To estimate the impacts of crop rotation changes, we first simulated the nitrogen, phosphorus, and soil sediment fluxes for each modeled crop type of corn, soybeans, and wheat following the method of Donner and Kucharik[8]. Nitrogen fluxes represented leaching past a soil depth of 1.5 m, whereas phosphorus and sediment fluxes reflected edge-of-field losses. We then multiplied the outputs for each crop by the change in rotational probability of each crop derived from the econometric model described above. For all non-corn (i.e. "other") crops including those not modeled, we estimated the water quality impacts as a weighted average of soybeans and wheat based on the planted area ratio of each within each county or region.

To simulate the impacts of cropland area change, we used the Agro-IBIS model to estimate the water quality outputs of specific cropland and noncropland classes for each individual patch of identified cropland expansion and abandonment. We then compared the median patch-level losses of N, P, and sediment for 2007-2016 between the cropland and noncropland simulations to estimate the differential impact of cropland area changes. These per-area differential impact values were then multiplied by the estimated areas of land use change due to the RFS2 within each major LRR region to estimate total impacts of the RFS2 due to cropland expansion and reduced abandonment.

References

1. Carter CA, Rausser GC, Smith A. Commodity storage and the market effects of biofuel policies. *Am J Agric Econ*. 2017;99(4):1027-1055.

2. Roberts MJ, Schlenker W. Identifying Supply and Demand Elasticities of Agricultural Commodities: Implications for the US Ethanol Mandate. *Am Econ Rev*. 2013;103(6):2265-2295. doi:10.1257/aer.103.6.2265

3. Hendricks NP, Sinnathamby S, Douglas-Mankin K, Smith A, Sumner DA, Earnhart DH. The environmental effects of crop price increases: Nitrogen losses in the US Corn Belt. *J Environ Econ Manag*. 2014;68(3):507–526.

4. Secchi S, Kurkalova L, Gassman PW, Hart C. Land use change in a biofuels hotspot: The case of Iowa, USA. *Biomass Bioenergy*. 2011;35(6):2391-2400. doi:10.1016/j.biombioe.2010.08.047

5. Lark TJ, Salmon JM, Gibbs HK. Cropland expansion outpaces agricultural and biofuel policies in the United States. *Environ Res Lett*. 2015;10(4):044003. doi:10.1088/1748-9326/10/4/044003

6. Li R, di Virgilio N, Guan Q, Feng S, Richter GM. Reviewing models of land availability and dynamics for biofuel crops in the United States and the European Union. *Biofuels Bioprod Biorefining*. 2013;7(6):666-684. doi:10.1002/bbb.1419

7. U.S. EPA. *Biofuels and the Environment: The Second Triennial Report to Congress.* Washington, DC: U.S. Environmental Protection Agency; 2018:159.

8. Donner SD, Kucharik CJ. Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proc Natl Acad Sci*. 2008;105(11):4513–4518.

9. Motew M, Chen X, Booth EG, et al. The Influence of Legacy P on Lake Water Quality in a Midwestern Agricultural Watershed. *Ecosystems*. 2017;20(8):1468-1482. doi:10.1007/s10021-017-0125-0

10. Gerber JS, Carlson KM, Makowski D, et al. Spatially explicit estimates of N2O emissions from croplands suggest climate mitigation opportunities from improved fertilizer management. *Glob Change Biol*. 2016;22(10):3383-3394. doi:10.1111/gcb.13341

11. Spawn SA, Lark TJ, Gibbs HK. Carbon emissions from cropland expansion in the United States. *Environ Res Lett*. 2019;14(4):045009. doi:10.1088/1748-9326/ab0399

12. Schnepf R, Yacobucci BD. Renewable Fuel Standard (RFS): overview and issues. *Congr Res Serv Wash DC*. 2010. http://www.pennyhill.com/jmsfileseller/docs/R40155.pdf. Accessed May 16, 2014.

13. Committee on Economic and Environmental Impacts of Increasing Biofuels Production; National Research Council. *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy*. Washington, D.C.: The National Academies Press; 2011.

14. Federal Registrar EPA. *Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule*.; 2010:14669-15320. https://www.gpo.gov/fdsys/pkg/FR-2010-03-26/pdf/2010-3851.pdf.

15. U.S. EPA. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. Office of Transportation and Air Quality, Assessment and Standards Division; 2010.

16. U.S. EPA. *Biofuels and the Environment: First Triennial Report to Congress*. ORD, National Center for Environmental Assessment; 2011.

17. National Research Council of the National Academies. *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy*.; 2011.

18. Hoekman SK, Broch A. Environmental implications of higher ethanol production and use in the US: A literature review. Part II–Biodiversity, land use change, GHG emissions, and sustainability. *Renew Sustain Energy Rev*. 2017. http://www.sciencedirect.com/science/article/pii/S1364032117306883. Accessed August 3, 2017.

19. Smith A. *Effects of the Renewable Fuel Standard on Corn, Soybean and Wheat Prices*. UC-Davis; 2018. https://arefiles.ucdavis.edu/uploads/filer_public/f1/4b/f14bb419-af5d-48f5-9032-4d966c759119/smith_-_effect_of_rfs_on_prices.pdf.

20. Pates N, Hendricks NP. *The Impact of the Renewable Fuels Standard on Corn Acreage*.; 2019. https://nphendricks.files.wordpress.com/2019/02/rfs_intensification.pdf.

21. Carlson KM, Gerber JS, Mueller ND, et al. Greenhouse gas emissions intensity of global croplands. *Nat Clim Change*. 2017;7(1):63-68. doi:10.1038/nclimate3158

22. U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016*. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016.

23. Keeler BL, Polasky S. Land-use change and costs to rural households: a case study in groundwater nitrate contamination. *Environ Res Lett*. 2014;9(7):074002. doi:10.1088/1748-9326/9/7/074002

24. Lark T, Bougie M, Spawn S, Gibbs H. *Cropland Expansion in the United States, 2008-2016*. University of Wisconsin-Madison; 2018:4. http://www.gibbs-lab.com/wp-content/uploads/2018/11/Land-conversion-research-brief_11.2.18.pdf.

25. Hendricks NP, Smith A, Sumner DA. Crop Supply Dynamics and the Illusion of Partial Adjustment. *Am J Agric Econ*. 2014;96(5):1469-1491. doi:10.1093/ajae/aau024

26. Woodard J. Big data and Ag-Analytics: An open source, open data platform for agricultural & environmental finance, insurance, and risk. *Agric Finance Rev*. 2016;76(1):15-26. doi:10.1108/AFR-03-2016-0018

27. USDA FSA. FSA Common Land Unit infosheet. April 2012. http://www.fsa.usda.gov/Internet/FSA_File/clu__infosheet_2012.pdf. Accessed July 15, 2015.

28. Yan L, Roy DP. Automated crop field extraction from multi-temporal Web Enabled Landsat Data. *Remote Sens Environ*. 2014;144:42-64. doi:10.1016/j.rse.2014.01.006

29. Boryan C, Yang Z, Mueller R, Craig M. Monitoring US agriculture: the US Department of Agriculture, National Agricultural Statistics Service, Cropland Data Layer Program. *Geocarto Int*. 2011;26(5):341-358. doi:10.1080/10106049.2011.562309

30. Soil Survey Staff NRCS United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for the United States. http://soils.usda.gov/technical/classification/scfile/index.html. Accessed May 7, 2013.

31. Daly C, Taylor GH, Gibson WP, Parzybok TW, Johnson GL, Pasteris PA. High-quality spatial climate data sets for the United States and beyond. *Trans ASAE*. 2000;43(6):1957.

32. Bloomberg L.P. *Local US Agricultural Spot and Commodity Futures Prices.* Bloomberg terminal

33. USDA. *2012 National Resources Inventory: Summary Report*. Washington, D.C.: Natural Resources Conservation Service ,; 2015. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf.

34. Hendricks N. *The Impact of the Renewable Fuels Standard on Cropland Transitions*. Kansas State University; 2018:8. https://nphendricks.files.wordpress.com/2018/11/rfs_extensification1.pdf.

35. Lark TJ, Mueller RM, Johnson DM, Gibbs HK. Measuring land-use and land-cover change using the U.S. department of agriculture's cropland data layer: Cautions and recommendations. *Int J Appl Earth Obs Geoinformation*. 2017;62:224-235. doi:10.1016/j.jag.2017.06.007

36. Gronberg JM, Arnold TL. *County-Level Estimates of Nitrogen and Phosphorus from Animal Manure for the Conterminous United States, 2007 and 2012*. US Geological Survey; 2017.

37. Brakebill JW, Gronberg JAM. County-Level Estimates of Nitrogen and Phosphorus from Commercial Fertilizer for the Conterminous United States, 1987-2012. 2017. doi:10.5066/F7H41PKX

38. Haines M, Fishback P, Rhode P. United States Agriculture Data, 1840 - 2012. 2014. doi:10.3886/ICPSR35206.v4

39. Laboski CA, Peters JB, Bundy LG. Nutrient application guidelines for field, vegetable, and fruit crops in Wisconsin. A2809. In: ; 2012. http://www.soils.wisc.edu/extension/pubs/A2809_06.pdf.

40. *IPCC Assessment Report 5: Anthropogenic and Natural Radiative Forcing*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013.

41. Poeplau C, Don A, Vesterdal L, et al. Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach. *Glob Change Biol*. 2011;17(7):2415-2427. doi:10.1111/j.1365-2486.2011.02408.x

42. Abatzoglou JT. Development of gridded surface meteorological data for ecological applications and modelling. *Int J Climatol*. 2013;33(1):121-131. doi:10.1002/joc.3413

43. Chaney NW, Wood EF, McBratney AB, et al. POLARIS: A 30-meter probabilistic soil series map of the contiguous United States. *Geoderma*. 2016;274:54-67. doi:10.1016/j.geoderma.2016.03.025

44. Gesch D, Oimoen M, Greenlee S, Nelson C, Steuck M, Tyler D. The national elevation dataset. *Photogramm Eng Remote Sens*. 2002;68(1):5–32.

45. Brown JF, Pervez MS. Merging remote sensing data and national agricultural statistics to model change in irrigated agriculture. *Agric Syst*. 2014;127:28-40. doi:10.1016/j.agsy.2014.01.004