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.

Contributing Authors: Tyler J. Lark[1], Nathan P. Hendricks[2], Nicholas Pates[2], Aaron Smith[3], Seth A. Spawn[1], Matthew Bougie[1], Eric Booth[1], Christopher J. Kucharik[1], and Holly K. Gibbs[1]

[1]University of Wisconsin-Madison; [2]Kansas State University; [3]University of California-Davis

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 nitrogen fertilizer application, 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 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}.

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.

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 and 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].

Our results show that this expansion of the RFS increased the price of corn in the U.S. by approximately 31% [80% Confidence Interval: 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].

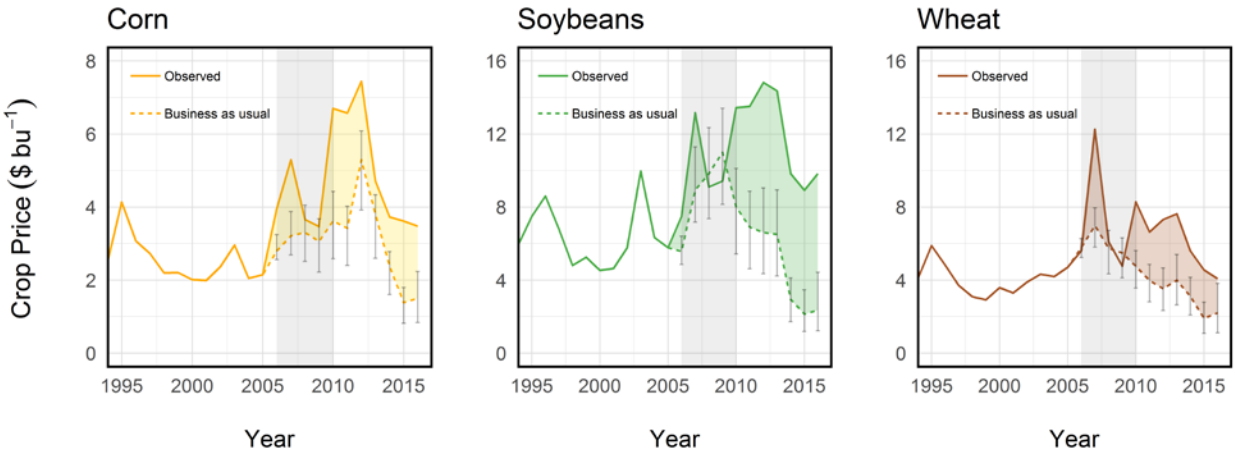

Figure 1: Observed and business-as-usual (BAU) estimates for the prices of corn, soybeans, and wheat. Vertical bars represent the 80% confidence intervals for each BAU spot price. Each year denotes a crop year, e.g., 2006 is Sep 2006 through Aug 2007 for corn and soybeans and June 2006 through May 2007 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 RFS 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 substantially 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.

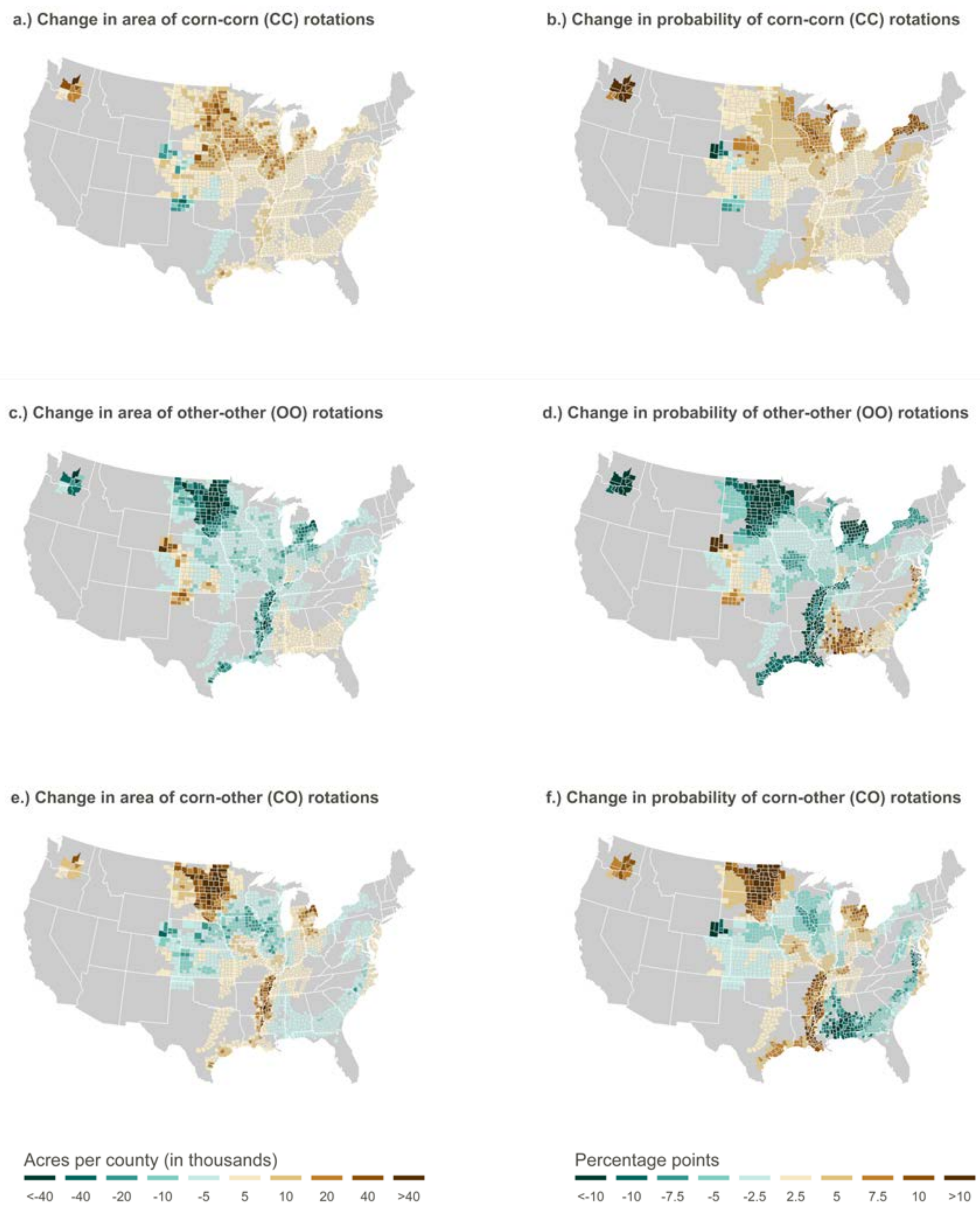

Figure 2: Changes in both absolute area (left column) and probability (right column) of continuous corn (CC), continuous other crops (OO), and corn-other crop rotations (CO) in the RFS2 scenario relative to business as usual.

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 either synthetic fertilizer or manure was applied to existing croplands on average each year between 2008 and 2016 (**Fig. 3**).

Increased use of N as a fertilizer is often associated with decreased groundwater and surface water quality, and can contribute to negative impacts such as eutrophication or hypoxia[3,8,21]. In addition, 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 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-RFS scenario. This represents roughly a 2-6% increase over existing N_2O emissions from all cropland[22,23].

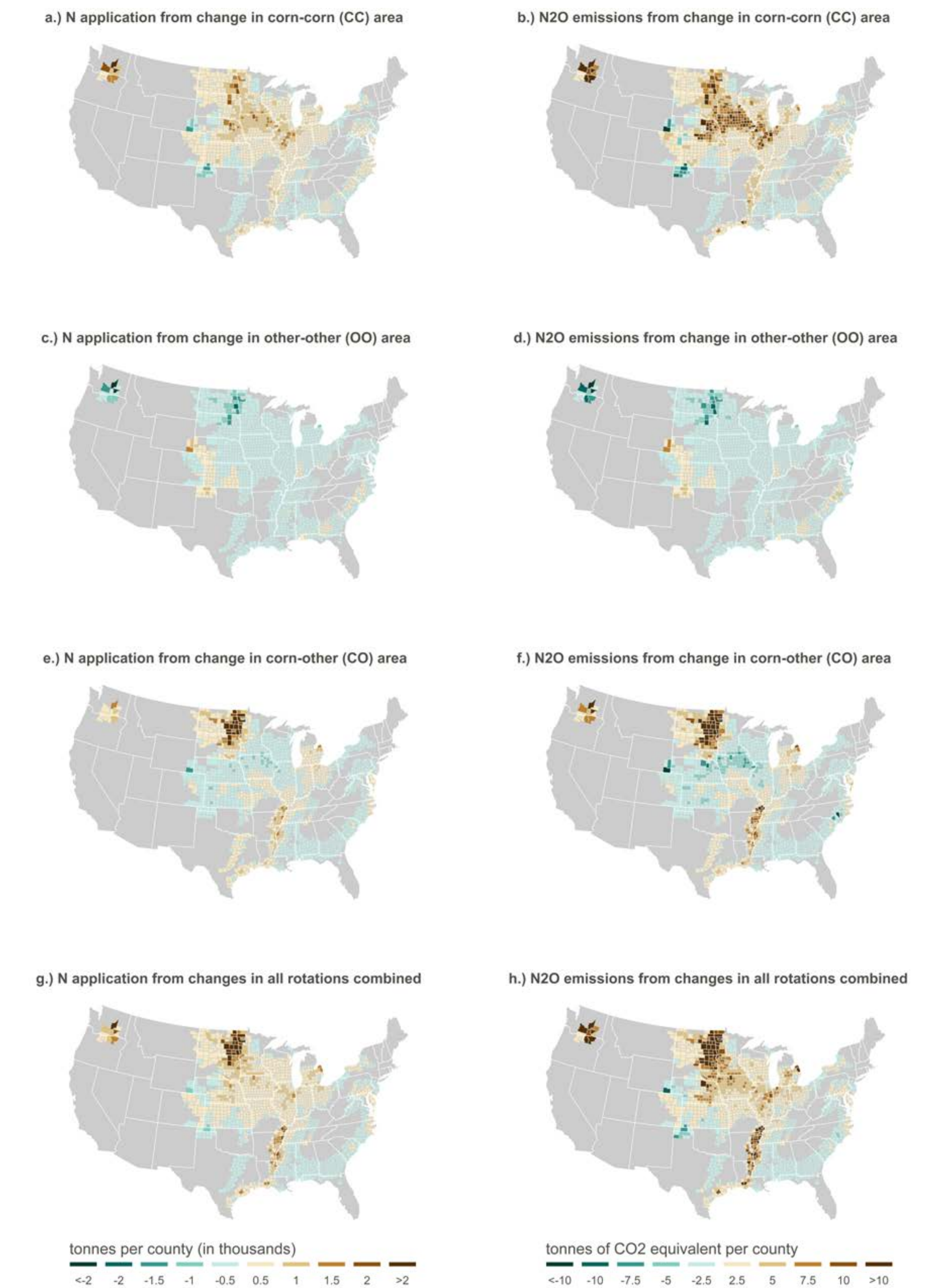

Figure 3: Changes in nitrogen (N) fertilizer application (left column) and associated nitrous oxide (N_2O emissions (right column) as a result of changes in area of continuous corn (CC), continuous other crops (OO),

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.

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 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 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. 4**). 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 RFS 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.

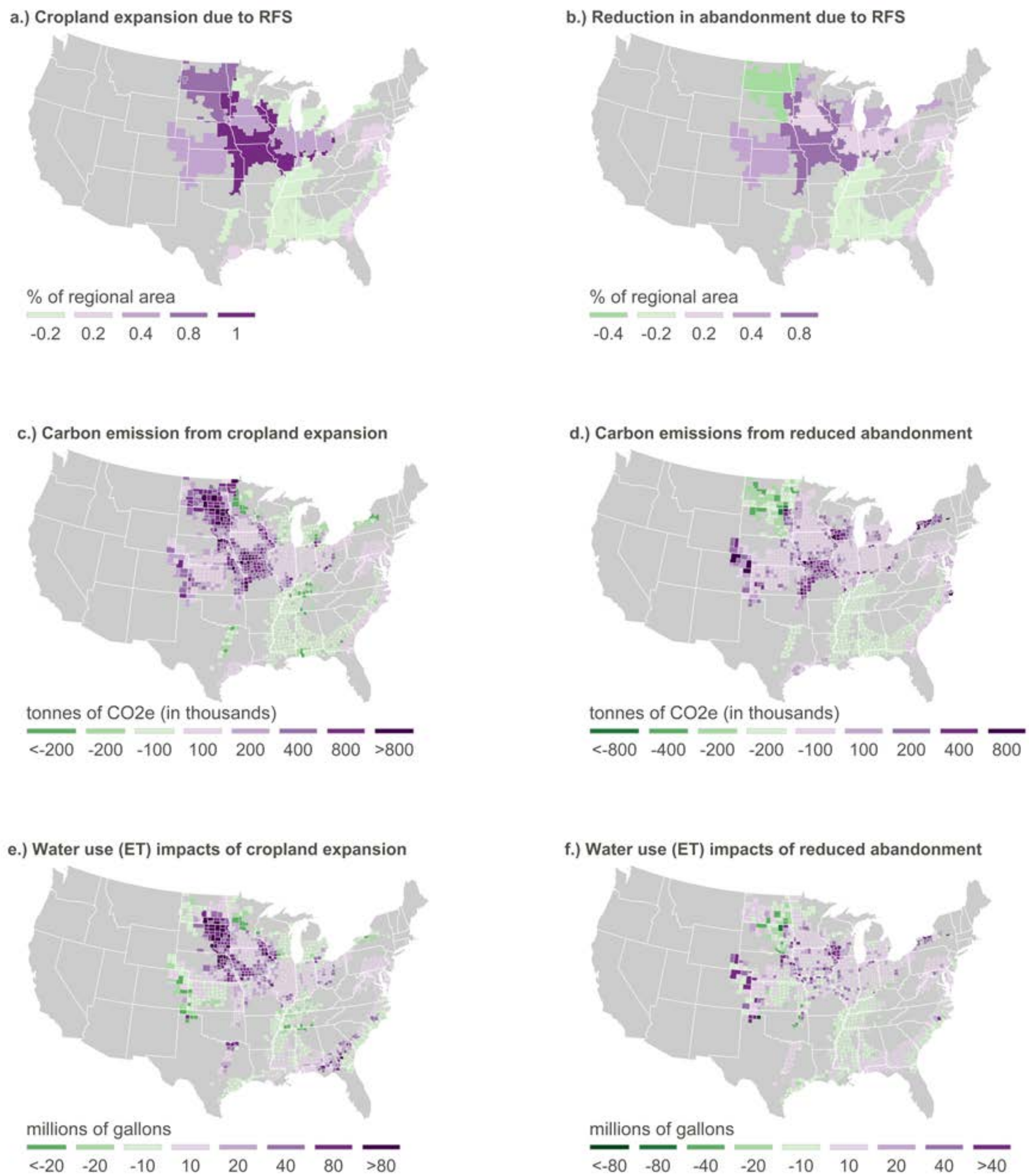

Figure 4: Change in cropland area, carbon emissions, and crop consumptive water use due to the expansion of cropland and reduction in abandonment associated with the RFS2.

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 RFS 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 RFS. This mixed data approach thereby combined the USDA NRI data's high certainty and long-term temporal coverage (prior to any RFS 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 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 RFS-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 RFS, 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 RFS, 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[33]. 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.

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