Comments on “Environmental Outcomes of the US Renewable Fuel Standard”

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Introduction

Lark et al. (2022) recently published “Environmental Outcomes of the US Renewable Fuel Standard” and addressed domestic land use change (LUC) of corn ethanol and associated greenhouse gas (GHG) emissions that are potentially caused by the U.S. Renewable Fuel Standard (RFS), as introduced in the 2005 Energy Policy Act and in the 2007 Energy Independence and Security Act (EISA). To do so, they considered the corn ethanol volume changes and LUC between 2008 and 2016[1].

In their assessment, Lark et al. assumed a business-as-usual (BAU) scenario (representing the goals of RFS1 for ethanol volume, as adopted in the 2005 Energy Policy Act by Congress, between 2008 and 2016), a new scenario (representing the goals of RFS2 for ethanol volume, as adopted in the 2007 EISA by Congress, between 2008 and 2016) to determine domestic LUC due to the RFS2. With no integrative modeling exercise, the authors simply calculated the average of the annual differences between the goals of RFS1 and RFS2 (5.5 billion gallons [Bgal]) and considered that volume of ethanol as the average annual contribution of RFS2 to new ethanol consumption between 2008 and 2016. Instead of using an integrated, coherent framework, as is the case with equilibrium models, in which changes in crop prices and associated LUCs at the intensive and extensive margin are determined simultaneously, Lark et al. applied a few loosely connected empirical methods to examine the impact of the RFS2 on three crops (corn, soybeans, and wheat). They estimated the short-term increases in commodity prices

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[1] In their main manuscript, Lark et al. referred to 2008 to 2016 as the eight years of their assessment time period. From this specification, it seems that the authors refer to changes in eight years of 2008, 2009, 2010, …, 2015. However, in various other places of their paper and supplemental information (SI), they referred to 2009-2016 as their study period. In this note we refer to changes in the eight years from 2008 to 2015, unless we quote Lark et al. and perform analyses where they clearly reference 2016 as the end year.

between 2008 and 2016 induced by the RFS2 and estimated that the prices of corn, soybeans, and wheat would increase by 30%, 20%, and 20%, respectively, due to an increase in the annual consumption of ethanol by 5.5 Bgal.

In the next step, Lark et al. used the Cropland Data Layer (CDL) from the United States Department of Agriculture (USDA) in combination with some other information on returns on cropland to estimate the probabilities of land transitions between cropland, pasture land, and Conservation Reserve Program (CRP) land. Using their projected increases in the prices of corn, soybeans, and wheat in combination with the estimated land transition functions, Lark et al. calculated that the area of corn plantation, adjusted for distiller's dried grains (DDG), would increase by 2.8 million hectares (Mha) due to the RFS2, and that would lead to an increase in cropland area by 2.1 Mha. They showed that an overwhelming share of land conversion due to the RFS2 would be conversion of CRP land to active cropland. Lark et al. assigned a set of significantly large land use emissions factors to the CRP land conversion and likely double counted the N_2O emissions in adding their LUC emissions to the rest of life-cycle analysis (LCA) emissions of corn-based ethanol, leading to the conclusion that the GHG emissions (commonly called carbon intensity) of ethanol are at least 24% higher than those of gasoline.

After a detailed technical review of the modeling practices and data used by Lark et al., we conclude that the results and conclusions provided by the authors are based on several questionable assumptions and a simple modeling approach that has resulted in overestimation of the GHG emissions of corn ethanol. In what follows, we present the general findings of our review.

Our review is organized in nine sections. In the first section we discuss their estimation of land conversions. The second section addresses systematic overestimation of soil organic carbon (SOC) changes by the authors. The issue of double-counting of N_2O emissions in the Lark et al. LCA is discussed in the third section. In the fourth section we refer to some inconsistencies in results provided by Lark et al. We then discuss misattribution of ethanol volumes to the RFS2 by those authors in Section 5. The assessment of impacts of yield improvement and DDG offsets on the demand for cropland are addressed in Section 6. The estimation of price impacts of the RFS is discussed in Section 7. Section 8 outlines deficiencies in modeling land transition. Finally, we conclude our findings in Section 9.

1. Land Conversions

Land use changes identified by Lark et al. are likely representing conversion of fallow/idle land to crops rather than conversion of permanent grasslands and thus is unlikely to result in a large carbon debt upon conversion.

Lark et al. stated "For the period 2008-17, we used the USDA-NASS Cropland Data Layer (CDL) and a look-up table to convert CDL land cover classes to vegetation types simulated by

AgroIBIS." We accessed the land conversion data layers in the SI of Lark et al. (Figure 1) and processed the data[2] as follows to see if we could produce results similar to those of Lark et al.

Because of limited time, we focused on two locations for our assessment experiment: Knox County, NE and Wayne County, IA (Figures 2 - 5). Both of these locations showed substantial conversions to cropland in Lark et al. The National Agriculture Imagery Program (NAIP) imagery for each available year from 2003 onward (usually every other year) was accessed via Google Earth Engine (GEE) for each polygon identified as "cropland expansion" individually. The GEE script also displays a plot for LandTrendr spatio-temporal curves of the Normalized Difference Vegetation Index (NDVI) for each polygon from 1984 to 2021. LandTrendr is an image segmentation program widely used in land change analyses developed at the University of Oregon. Each point on the curve is the average NDVI value for the displayed polygon for spring, summer and fall for each year. Finally, we compared the results from the NAIP imagery and LandTrendr curves against Lark et al. to determine if there were indications of that polygon being cropland in the past (Figures 2 - 5).

We found that cropland typically has a sharp increase in NDVI from spring to summer, and then a sharp decline from summer to fall. Grassland or fallow land has higher NDVI values in the spring and fall, but lower summer values. Our comparison showed that fields that are identified by Lark et al. as expansion to cropland may often be short-term fallow/idle lands (less than 10 years).

Further, we overlaid the LandTrendr curves with prevailing corn crop prices (Figures 4 and 5). We find that there is agreement between a temporary increase in corn crop prices and a change from fallow/dormant to production agriculture. These parcels identified by Lark et al. in their "Cropland Expansion Layer" appear to be prime examples of land on the margin that is toggling between agriculture and fallow/idle states based on crop price signals.

As a result, their estimates of land conversion would not likely result in the large carbon debt assumed by Lark et al. for these parcels because the employed carbon response functions (CRFs) for SOC changes should not be applied to soils that have been previously cultivated, as stated by the authors themselves (see Section 2 below). This would likely result in a systemic overestimation of SOC changes for these parcels.

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[2] First, we accessed data via https://zenodo.org/record/3905243#.YjeNMOrMJPb and downloaded the geodatabase of US_land_conversion_2008-16.gdb.zip. Second, we opened layer "ytc" (which is described on the webpage as areas in cropland expansion "areas converted to crop production between 2008 and 2016" with the year of expansion listed in the polygon) in ArcGIS software. Third, we loaded Lark et al. "cropland expansion" layer into Google Earth Engine (GEE) (See Figures 1-5) using a GEE javascript.

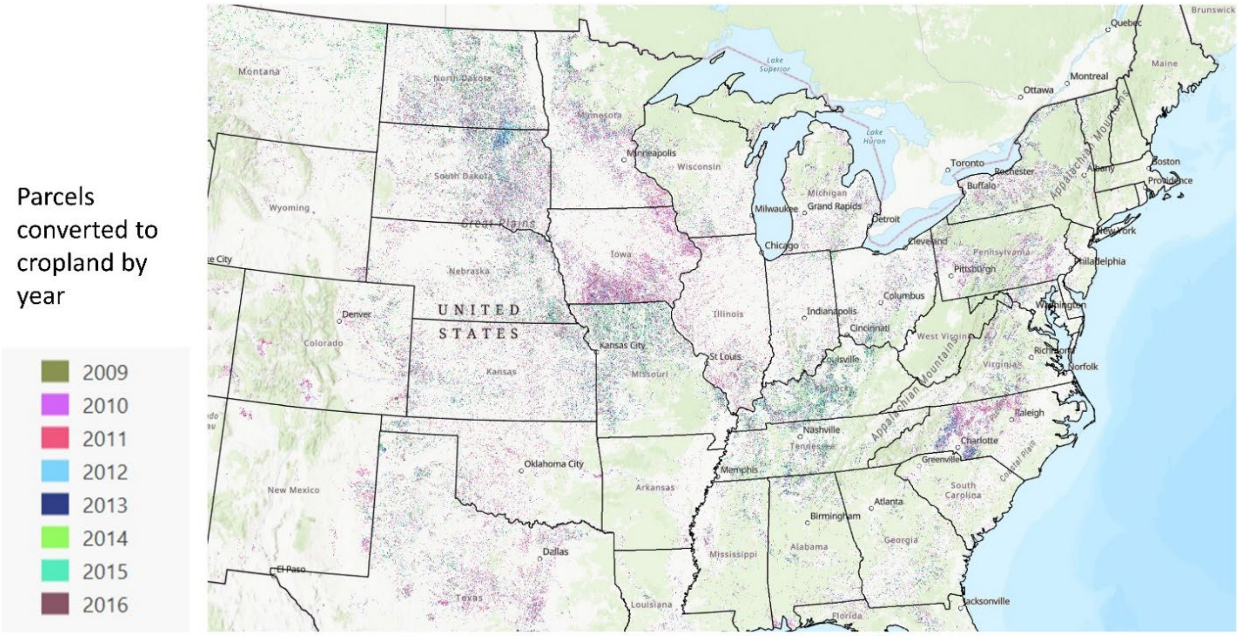
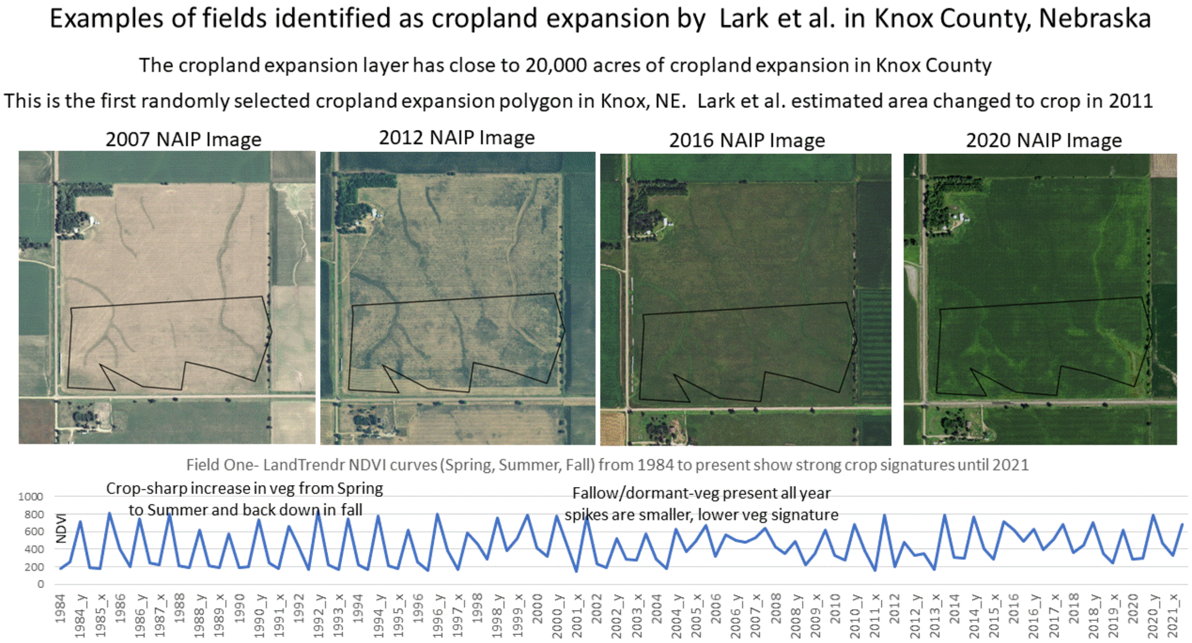


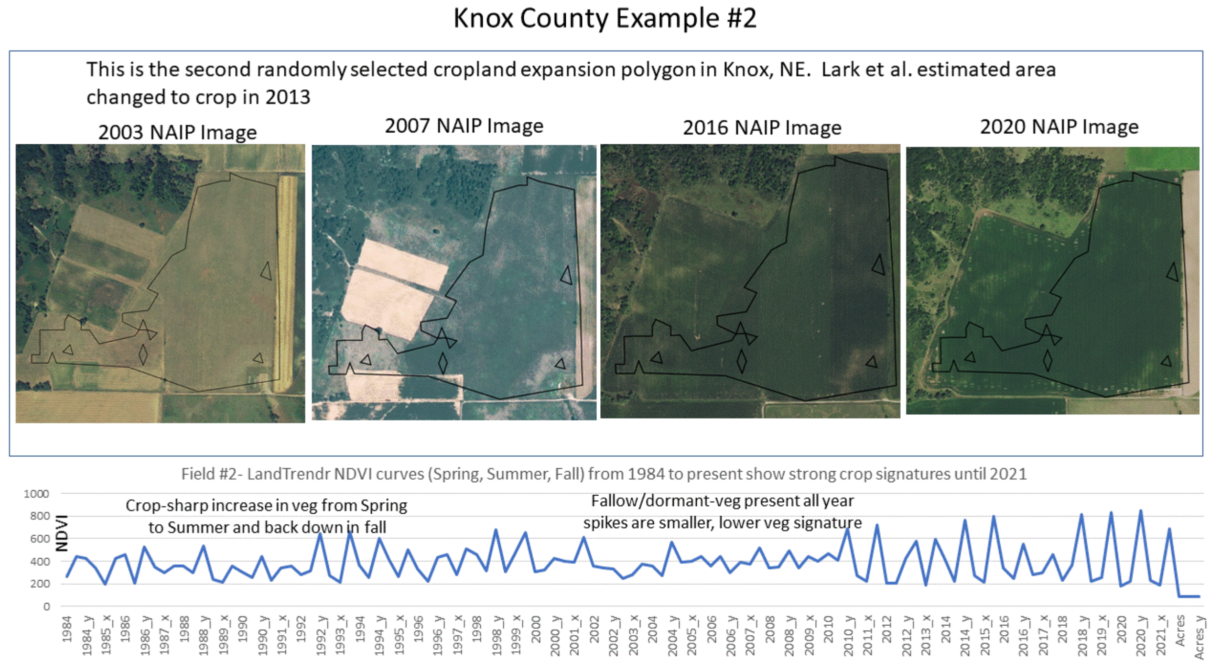
Figure 1: Lark et al. cropland expansion layer


Examples of fields identified as cropland expansion by Lark et al. in Knox County, Nebraska

The cropland expansion layer has close to 20,000 acres of cropland expansion in Knox County

This is the first randomly selected cropland expansion polygon in Knox, NE. Lark et al. estimated area changed to crop in 2011

Figure 2: Knox County (NE) Location 1: Comparison of Lark et al. predicted LUC against NAIP and LandTrendr


Knox County Example #2

This is the second randomly selected cropland expansion polygon in Knox, NE. Lark et al. estimated area changed to crop in 2013

Figure 3: Knox County (NE) Location 2: Comparison of Lark et al. predicted LUC against NAIP and LandTrendr

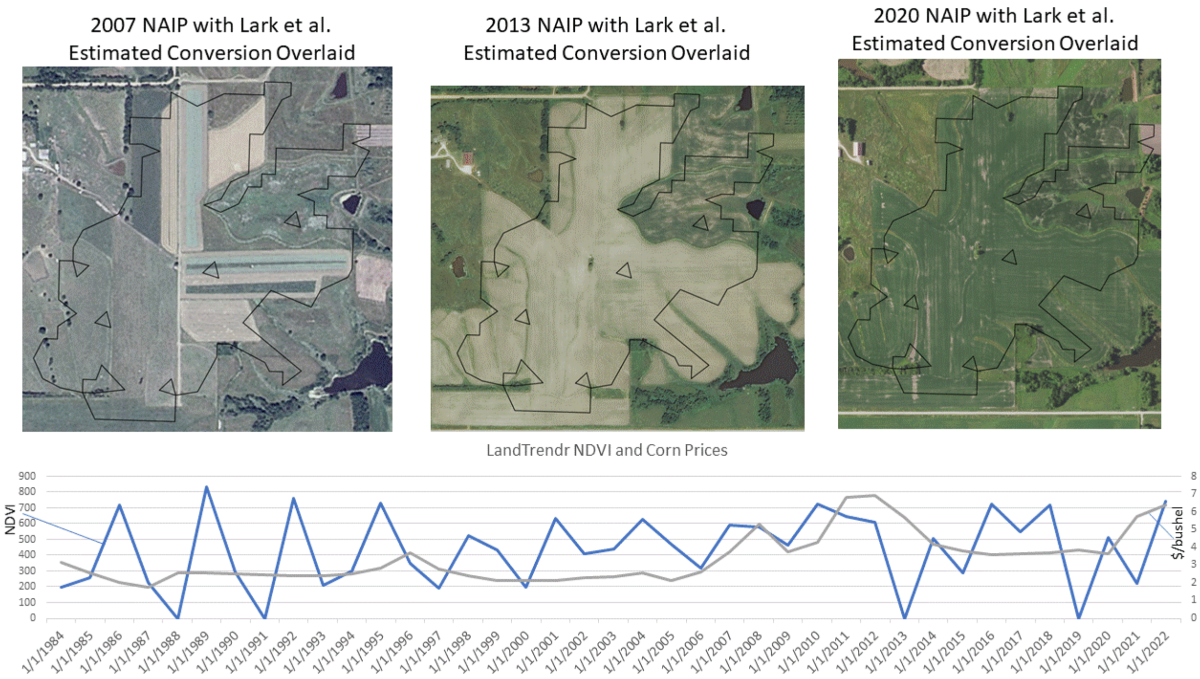


Figure 4: Wayne County (IA) Location 1: Comparison of Lark et al. predicted LUC against NAIP, LandTrendr, and Corn Prices

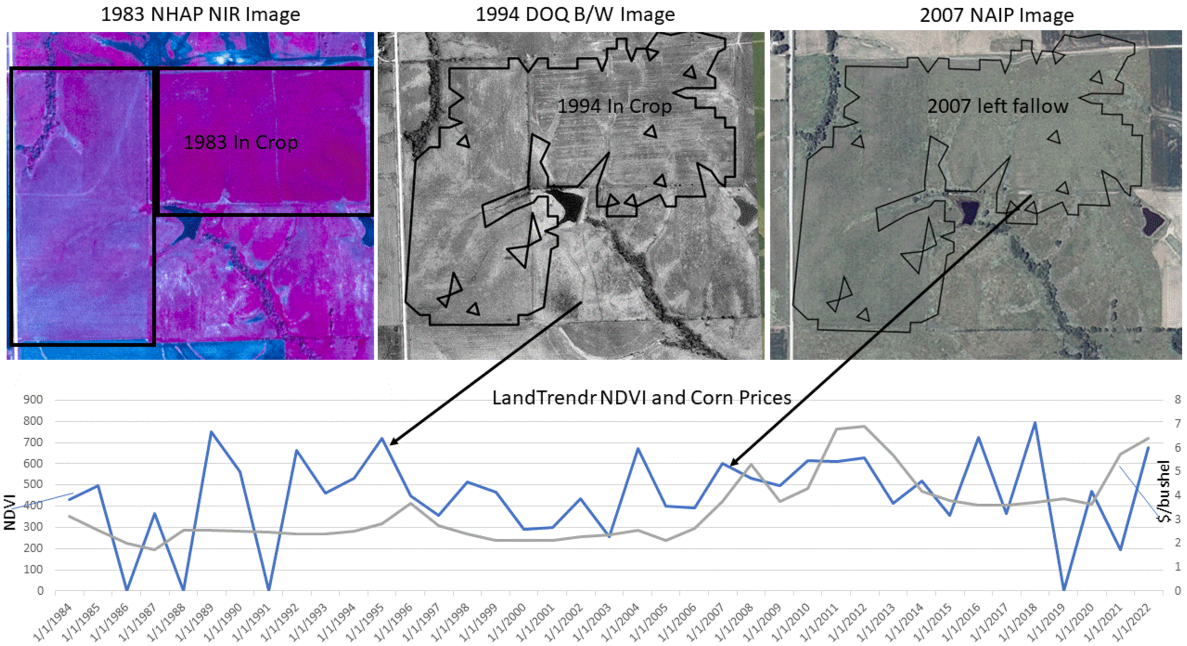


Figure 5: Wayne County (IA) Location 2: Comparison of Lark et al. predicted LUC against National High-Altitude Aerial Photography (NHAP), Digital Orthophoto Quadrangle (DOQ), NAIP, LandTrendr, and corn prices

Besides estimating land conversions for ethanol production, Lark et al. established a counterfactual scenario in which they assumed CRP enrollment would have increased and a certain amount of cropland would be converted to pastureland if the RFS2 was not adopted. However, CRP enrollment is decided by Congress with authorized funding for CRP. In fact, CRP enrollment declined in the past 15 years because of reduced CRP fund. The high level of CRP enrollment (13 Mha) could not have been maintained after 2010 without government payments to support it, even if there was no RFS2.

2. Systemic Overestimation of Soil Organic Carbon Changes

Lark et al. likely overestimated soil carbon loss by a factor of two to eight for land use change by apply carbon response functions that are relevant for conversion of native or undisturbed grassland to cropland and not for CRP and cropland pasture to cropland.

To estimate the ecosystem carbon emissions associated with RFS2-related LUC, Lark et al. followed the "stock difference" method adopted in their co-authors' earlier article (Spawn et al., 2019). For that method, pre-conversion SOC stocks were first derived from U.S. soil maps (Ramcharan et al. 2017) and then post-conversion SOC stocks were modeled by applying "carbon response functions (CRFs)" (Poeplau et al. 2011) that describe the expected proportional change in the size of pre-conversion SOC stocks. We have identified two major issues with the authors' analysis. Each of these issues may lead to overestimating SOC changes.

First, Lark et al. stated that their model predictions were similar to those observed after conversion of CRP land when managed with conventional tillage. However, Lark et al. applied the CRFs that were based on conversion of 'native' or undisturbed grassland to cropland. CRP land is likely to be less rich in soil carbon stocks than native or undisturbed grassland because it has been under vegetation cover for only a limited number of years. Additionally, treating all land that converted to cropland as being from CRP instead of from cropland pasture or fallow/idle land may be incorrect for reasons explained in Section 1. Appendix A provides more details on changes in the area of CRP land over time. The CRFs account for the impacts of abiotic factors (i.e., annual precipitation and temperature, soil depth, and texture) on soil carbon emissions, but do not account for recent or frequent transitions of land parcels between different uses, such as 'cropland pasture' or into and out of CRP. In a previous paper, some of the authors pointed out that "by applying these CRFs to soils that may have been previously cultivated, our approach may overestimate the sensitivity of some soils to conversion" (Spawn et al. 2019) but Lark et al. did not elaborate on this potential overestimation or assessed how it could influence their findings.

Second, the validation of the SOC emissions model used by Lark et al., which was published in a previous paper (Spawn et al. 2019), showed remarkably poor fit to measured SOC changes. Among the dozens of sites used for validation, many observed values appear evenly distributed between 0 – 20 Mg/ha SOC emissions (see the original authors' figure reproduced below [Figure 6]). The modeled (predicted) values show a very different distribution. No modeled values fall between 0 – 10 MgC/ha SOC emissions, and only a small fraction falls between 10 – 20 MgC/ha. We extracted the data points for grassland-to-cropland conversion at 10 cm and 30 cm depths to assess the model fit (Figure 6). As shown below, the model tends to overestimate SOC emissions by about 20 MgC/ha at lower observed values and is poorly correlated with observations in general. Our re-analysis shows that the model used by Lark et al. does not accurately assess SOC emissions.

Spawn et al. (2019) also noted that "model fit was significantly inferior for former grasslands managed with no-tillage," indicating that the model may not be suitable for lands managed with low-till, no-till, or other conservation practices. The apparent result of our re-analysis is that the SOC emissions model used by Lark et al. may overestimate soil carbon loss by a factor of two to eight for lands with smaller changes in soil carbon (Figure 6), particularly those not managed using conventional tillage. Both of these criteria may apply to the land parcels that are the focus of analysis by Lark et al., lands with a history of cycling between cropland, pasture, and CRP.

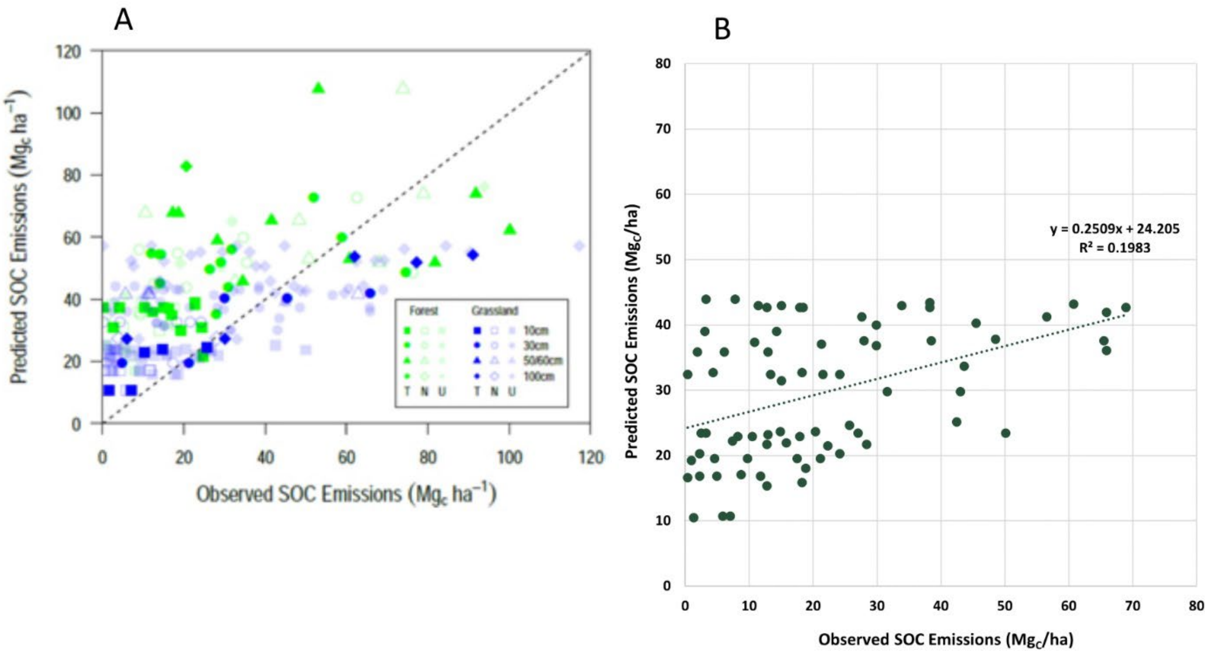


Figure 6: A reproduction of Figure 4 from ‘Carbon emissions from cropland expansion in the United States’ by Spawn et al. (2019), presented by the original authors as a “validation of SOC emission estimate from forest (green) and grassland (blue) conversion estimates” (A). Extracted data points for grassland-to-cropland conversion at 10 cm and 30 cm depths shown separately (B). It appears to us that the model is skewed toward higher SOC estimates than were observed at many locations.

The literature/data on SOC of CRP land is very sparse. This is why USDA recently launched a new initiative (First Phase of Soil Carbon Monitoring Efforts through Conservation Reserve Program Initiative) to sample, measure, and monitor soil carbon on CRP acres to better quantify the climate outcomes of the program. This initiative will provide observational data of SOC dynamics to reduce uncertainties from any modeling approaches to estimate forgone SOC accumulation. Without such observational data to support their estimates, Lark et al. should at least have conducted an uncertainty analysis of their SOC effects in land conversion.

3. Double-counting of N_2O Emissions and Omissions of Avoided Emissions

Lark et al. appeared to have double-counted the N_2O emissions with fertilizer use for corn farming by adding 9 gCO_2e/MJ of ethanol to the remaining LCA results of corn ethanol and overlooked that these were already included in the corn farming related emissions as is the case in most LCA calculations, such as those from the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model.

Lark et al. included N_2O emissions from incremental nitrogen fertilizer applications in their study. In fact, they concluded the additional N_2O emissions induced by the RFS2 was 9 gCO_2e/MJ of ethanol. The authors first estimated county-level rates of nitrogen by compiling the data from the US Geological Survey, the Census of Agriculture, and university extension publications. Then, they used these rates to calculate additional nitrogen usage (synthetic fertilizer and animal manure) associated with the change in crop rotation or cropland area due to RFS2, followed by the modeling of the changes in N_2O emissions from the additional fertilizer usage.

Most corn ethanol LCA studies account for N_2O emissions from nitrogen fertilizers in corn farming using emission factors, which assume linear/non-linear relationships between N_2O emissions and nitrogen inputs. This is the same approach employed in LCA studies and in Lark et al. However, what they missed in their calculation of additional N_2O emissions is that if there is any change in nitrogen applied to corn, the farming emissions would have already included the GHG impact of such a change, which is especially true for those LCA studies on total U.S. ethanol volume such as 15 Bgal.

For example, GREET utilizes USDA fertilizer data through 2018 that already reflect what is practiced in the field (new land with lower yield, increased corn on corn-soybean rotation, as well as increased yield per bushel of corn harvested on existing corn farms). That is, GREET LCA and other LCA, with up-to-date N fertilizer use data to reflect the state of U.S. corn farming including RFS effect. Thus, the inclusion of 9 gCO_2e /MJ due to additional fertilizer usage by Lark et al., as shown in Figure 3 of their paper, appears to be double counting the corn farming related GHG emissions because they added this value to the emissions of the rest of LCA for corn ethanol obtained from the three studies included in their Fig. 3 which likely already included their emissions. Removing the 9 gCO_2e/MJ from fertilizer emissions to this potential double-counting reduces the Lark et al. estimate for LUC emissions by 23% from 38.7 to 29.7 gCO_2e/MJ.

Additionally, Lark et al. noted the adverse implications for food production due to ethanol production and the displacement of soybeans and wheat in their modeling exercise. However, they did not appear to account for GHG emissions savings as a result of reductions in food consumption as a result of grain price increases. If less food crops are produced due to ethanol, then the avoided emissions from these should have been accounted for. Finally, the mix of meat production has changed in favor of pork and poultry over beef due to feed availability induced by biofuel production (Taheripour et al., 2021). This has generated large emissions savings and contributed to the observed reduction of GHG emissions associated with the U.S. agricultural sector. The LCA approach used by Lark et al. neglected these avoided emissions.

4. Inconsistencies in Results Obtained by Lark et al.

We note several findings reported by Lark et al. that are difficult to rationalize, as we illustrate in Figure 7. First, consider Panel A of Figure 7, which shows the projected changes in carbon intensity (CI) in cropland by county obtained from the Lark et al. results presented in their Figure 2. **Panel A of Figure 7 reveals inexplicably negative CIs. Why are there negative changes in CI per hectare in cropland?** When cropland increases, with no improvement in SOC due to land management or high carbon crops, carbon emissions should also increase, and when cropland declines, carbon emissions should decrease. A negative CI implies an error and that the results were not reviewed for accuracy. This figure also reveals extremely large values of the examined ratio up to more than 12 Gg CO_2e/ha. These extreme CI values per hectare of land are not explained or justified.

Next, consider Panel B of Figure 7. This figure again represents the changes in carbon over the changes in cropland by county, with caps of ±1 Gg CO_2e/ha that we placed on the Lark et al. results to better display the distribution of the CIs across counties. This figure shows a major variation in the calculated ratio across counties. Given that the estimated changes in cropland area by them are mainly related to the changes in CRP land across counties, what justifies the huge variations in CIs across counties (between –1 to +1 Gg CO_2e/ha)?

In Panel C of Figure 7, we compare the ratio of the projected changes in cropland area to the projected changes in corn area by country, obtained from Lark et al. results presented in their Figure 2. Panel C of Figure 7 reveals odd results. **This figure shows that Lark et al. projected that, in some counties, the area of cropland would increase up to more than 2,000 hectares for one hectare of change in corn area. What justifies these extremely large changes at the extensive margin?**

Panel D of Figure 7 again represents the ratio of the projected changes in cropland area over the projected changes in corn area by country, with caps of ± 30 hectares, which we placed on Lark et al. results to better reveal the distribution of cropland area over corn area ratio. **This figure indicates that, in many counties, one hectare of change in corn area generates up to 30 hectares of change in cropland area. What justifies these substantial changes? Again, these large changes suggest that Lark et al. overestimated the land transformation elasticities.**

Lark et al. projected that the area of corn increases in 1,353 counties and decreases in 349 counties. In addition, their results show changes in cropland in 126 counties but with zero change in corn area. These changes strongly suggests that the Lark et al. modeling approach reshuffles geographic location of crop production. It moves corn from one location to another location and does the same for other crops. While changes in different crops among geographic locations have some minimal SOC changes, it is not clear to us whether Lark et al. approach **magnifies the demand for land conversion for crops without carefully address cropland reshuffles.**

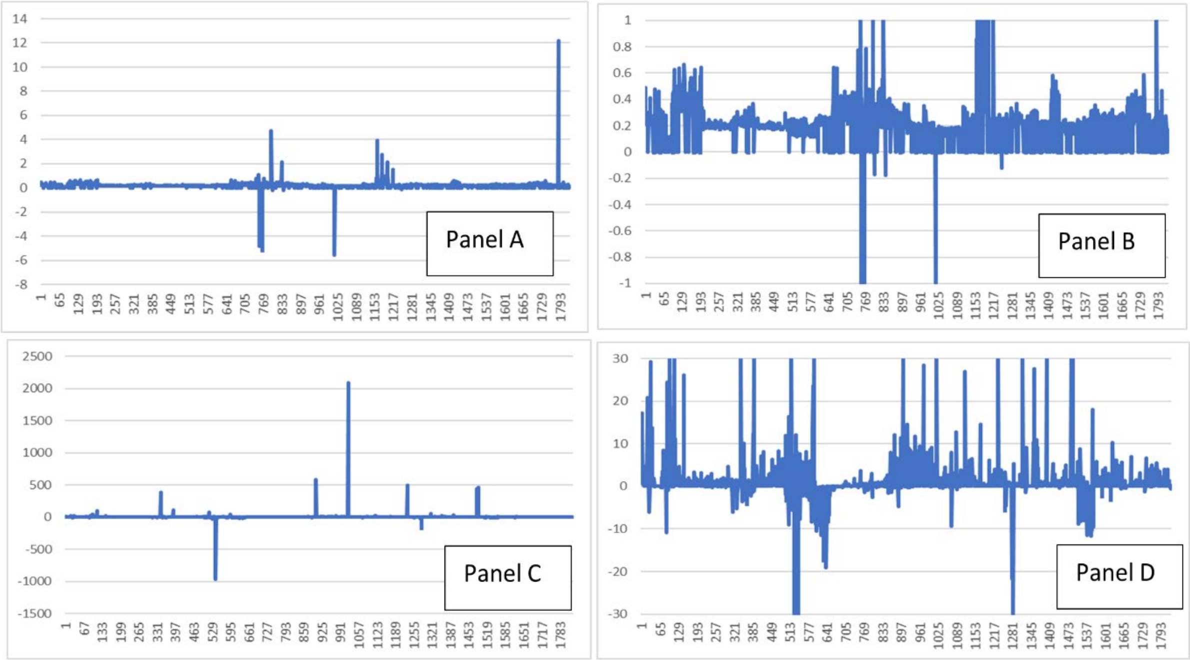


Figure 7. In-explicable findings from the SI in Lark et al. Panel A: Ratio of changes in carbon emissions to changes in cropland in Gg CO_2e/ha. Panel B: Ratio of changes in carbon emissions to changes in cropland in Gg CO_2e/ha with cap between – 1 to +1. Panel C: Ratio of changes in cropland over changes in corn area in ha /ha. Panel D: Ratio of changes in cropland over changes in corn area in ha /ha with cap between –30 to +30.

5. Misattribution of Ethanol Volumes to the RFS2

Lark et al. attributed 5.5 Bgal of ethanol per year to RFS2 between 2008 and 2016 by comparing the volume under RFS2 and RFS1 without considering other drivers of ethanol production. The expansion in the biofuel industry (including corn ethanol and other biofuels), even in the short time period from 2008 to 2015, occurred due to many drivers, including but not limited to changes in non-RFS biofuels supporting policies (such as ban of MTBE in gasoline blends but needed oxygenate in gasoline blends and tax credits), changes in crude oil price, changes in demand for gasoline, the 10% blend rule and the blend wall issue, changes in livestock industry and its demand for feed crops and other feeds (e.g., DDG and meal products).

6. The Amount of LUC Attributed to Corn Ethanol Without Careful Consideration of Yield Increase and DDG Offsets

Lark et al. stated: "We found that the RFS stimulated 20.8 billion L (5.5 Bgal) of additional annual ethanol production, which requires nearly 1.3 billion bushels of corn after accounting for coproducts that can be fed to animals." In their SI, Lark et al. further stated (page 5): "About one-third of each corn kernel that enters an ethanol plant is recycled as DDG, which are used for animal feed and have a price similar to corn grain. The other two-thirds of the kernel — the starch — is converted to ethanol."

In the following analysis, we test how much land expansion could be expected given yield increases over the considered time frame as well as land offsets provided by DDG animal feed. Since DDG both offset corn and soybean meal in animal feed rations, this nexus was taken into consideration. The methodology of this analysis is documented in our 2020 paper titled "Assessment of the National Resources Inventory (NRI), the Census of Agriculture, the Cropland Data Layer (CDL), and Demand Drivers for Quantifying Land Cover/Use Change" which is posted on the USDA website and was originally prepared for the U.S. Environmental Protection Agency (Pearson et al. 2020). This approach only uses documented acreage and yield data for corn and soybeans, which is being assessed by USDA with high accuracy. It is therefore not subject to the uncertainties inherent in remote sensing-based LUC analyses of non-croplands and differences in land cover definitions between data sets (Copenhaver 2021, Wang 2022).

Gross acres needed for ethanol production: Lark et al. assume 5.5 Bgal of ethanol stimulated by RFS2. This volume would require 1.897 billion gross bushels of corn, while simultaneously producing 15.187 million tons of DDG (at 2016 plant efficiencies of 2.9 gallons/bushel of ethanol and 5.52 lbs/gallon of DDG). At the prevailing corn yield of 174.6 bu/acre in year 2016, the production of the 5.5 billion stimulated gallons would require an additional 10.862 million gross acres.

Acres offset from DDG: The amount of DDG production was converted into total acres needed to produce equivalent amounts of livestock and poultry feed (at 2016 yields) and the results of these calculations are shown in Table 1. We used DDG displacement ratios developed in the GREET model as well as published soybean processing yields of 79.2% for soybean meal, 17.8% for soybean oil, and 3% for waste (Lusas 2004). We calculate acres offset from DDG production to a total of 5.539 million acres.

Table 1: Millions of Acres Offset from DDG Production.

DDG Production (Short Tons)	**15,188,000**
GREET DDG Corn Displacement Rate	0.763
GREET DDG Soy Meal Displacement Rate	0.313
DDG Corn Equivalent - Area Harvested Credit (Million Acres)	2.370
DDG Soybean Equivalent - Area Harvested Credit (Million Acres)	3.169
Total Credit from DDG (Million Acres)	5.539

Acres spared by yield increases: In 2008, 78.570 million acres of corn were harvested with an average yield of 153.3 bushels/acre, producing 12.044 billion bushels of corn (USDA Quick Stats). Applying the 2016 corn yield of 174.6 bu/acre to this acreage footprint would produce 13.718 billion bushels of corn, an increase of 1.674 billion bushels that results in -9.585 million surplus acres due to yield increases.

Results: Table 2 summarizes the results from both DGS production and corn yield increase. Our analysis shows that (without ethanol production) yield increases since 2008 would have reduced base year 2008 corn acres by 9.585 million acres. However, incremental ethanol production demanded a gross acreage of 10.862 million acres, which is higher than the land spared from yield increases. However, taking the acreage offset from DDG production of 5.539 million acres into account still results in an overall land area spared on 2008 corn acres of 4.262 million acres. This suggests that given the yield increases, the additional demand for ethanol is unlikely to have led to large increase in cropland estimated by Lark et al. Instead, other factors including urban development may have shifted the corn footprint around.

Table 2: Summary of Results of Potential Net Corn Acreage.

Base Year	**Acres**
1. Gross acres needed for increased ethanol volume	+10,862,266
2. Land area spared from DDG production	-5,539,158
3. Land area spared from corn yield increases on 2008 corn acres (no ethanol production)	-9,585,000
4. Net land area (1+2+3) after considering DDG with ethanol production and corn yield increases on 2008 corn acres	-4,261,892

7. Estimation of Price Effects of the RFS2

The validity of picking the time period of 2006-2010 to assess price impacts with the 5.5 Bgal for RFS2 between 2008 and 2016 is questionable.

Lark et al. estimated Vector Auto-Regression (VAR) equations to assess the price impact of the RFS2 and project a uniform increase of 30% of corn, 19% for soybeans and wheat over time. This is contrary to findings by other **recent work developed by Filip et al. (2019) who reviewed the existing literature in this area and estimated the price impacts of biofuels for eight commodities in the U.S., the EU, and Brazil using the VAR approach and detailed weekly data (instead of annual data). Filip et al. (2019) concluded that "*price series data do not support strong statements about biofuels uniformly serving as main leading source of high food prices and consequently the food shortages.*"**

Note that we were not able to find the Lark et al. estimated price equations and their validation tests and statistics in their paper or SI.

Lark et al. evaluated the price impact of 5.5 Bgal by using the observed prices for the 2006-2010 period to evaluate the price impacts while their assignment of 5.5 billion gallons to the RFSs is for the first eight years between 2008 and 2016. During 2006-2010 crop prices increased significantly, but these prices dropped in the following years and came back to much lower levels. The SI of Lark et al. states, "*We estimated the effects of the RFS on corn, soybean, and wheat prices by comparing observed prices in the 2006-10 crop years to the BAU projections for those years. Table S1 shows that corn prices exceeded the BAU by 31%, soybean prices by 19%, and wheat prices by 20% in 2006-10*".

We reviewed the observed wholesale prices of corn, soybeans, and wheat using Food and Agricultural Organization (FAO) data in Table 3. This table shows that average annual changes in the prices of corn, soybeans, and wheat were about 23.9%, 16.7%, and 13.9%, respectively, from 2006 to 2010. The corresponding averages for 2008 to 2015 were 0.8%, -0.6%, and -1.8%, respectively. Note the one can compare Figure 1 from Lark et al. with Figure 8 from this paper and verify that the FAO data and Lark et al. data on the examined crop prices represent similar patterns over time. Thus, their approach of projecting that crop prices increased by a uniform 31% for corn, 19% for soybeans and 20% for wheat over the entire 2008-2016 period does not appear to be justified or supported by observed data.

Table 3: Wholesale prices for corn, soybeans, and wheat: 2006 to 2015[3]

year		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average of annual % changes	
												2006-10	2008-15
Wholesale prices $/Bushel	corn	2.36	2.06	2.49	2.26	3.25	3.56	2.44	1.93	1.83	1.85	-	-
	Soybeans	5.58	5.55	6.40	5.47	6.72	6.72	6.48	4.93	4.63	4.55	-	-
	Wheat	2.91	3.24	3.27	3.46	4.55	4.76	3.37	2.64	2.48	2.61	-	-
Annual % changes	corn	51.9	37.5	-3.0	-12.5	45.7	20.1	10.6	-35.1	-17.0	-2.7	23.9	0.8
	Soybeans	13.5	57.2	-1.3	-3.8	17.9	10.6	15.3	-9.6	-22.4	-11.3	16.7	-0.6
	Wheat	24.6	51.6	4.6	-28.1	16.8	27.3	7.5	-11.9	-12.7	-18.2	13.9	-1.8

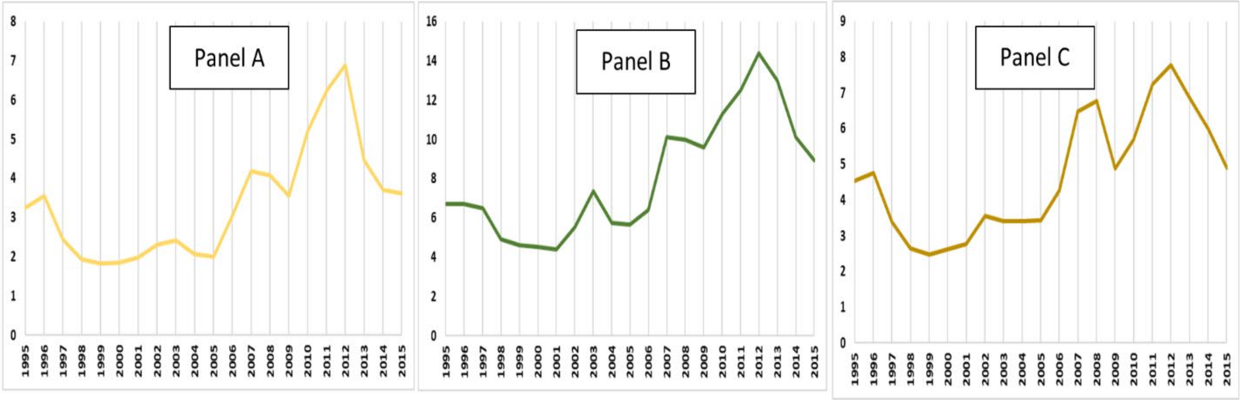


Figure 8: Wholesale prices of crops in $/bushel. Panels A, B, and C show wholesale prices of corn, soybeans, and wheat, respectively.

8. Modeling Land Transition

Lark et al. did not recognize cropland pasture as a sub-category of cropland in their analyses and perhaps treated this type of land as pasture land or fallow land. This misidentification and the method used by the authors to assess land return is likely to have

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[3] Based on data from FAOSTAT.

artificially led to the additional demand for active cropland being met largely by CRP land and not by cropland pasture.

To satisfy the additional demand for active cropland, Lark et al. considered two sources: CRP and pasture land. Their results shows that CRP has a large share in the land conversion. However, there are, in fact, three choices to increase active cropland:

i. Conversion of CRP land to active cropland,
ii. Conversion of cropland pasture to active cropland,
iii. Conversion of pasture land to active cropland,

Consider now the choice between CRP and cropland pasture. If CRP is still under contract, that land will not be a choice to be transferred to cropland. If the CRP land is out of contract, then the choices are converting the CRP land with no contract, converting available cropland pasture, or converting a portion of each. Then the choice between pasture land and the bundle of "CRP-cropland pasture" will depend on their expected returns.

It is important to distinguish between cropland pasture (that transitions frequently between crop and pasture) and pasture land (or permanently fallow land) because the return on returning cropland pasture to cropland will be similar to CRP and much higher than the return on converting pasture land to cropland. For details see Appendix A. Since cropland pasture is unlikely to be very rich in soil carbon stocks, its conversion leads to a low carbon debt.

9. Conclusions

Over the past 15 years many papers have studied LUC due to biofuel production and policy. In the absence of any observed evidence, some early papers published on this topic claimed that producing ethanol in the U.S. would generate major deforestation in the country and elsewhere and that the emissions associated with the conversion of natural land to cropland would cause GHG emissions that would increase the carbon intensity of ethanol to a level higher than the carbon intensity of gasoline. Over time various studies showed that those early papers overstated the magnitude of deforestation due to biofuels. The more advanced analyses, relying on the recent actual observations on land use changes, showed that intensification in crop production due to yield improvement and cultivation of idled cropland, and shifting demand form unwanted feed crops to biofuels by-products have jointly eliminated the need for conversion of natural land to cropland for biofuel production and hence provided significantly lower estimates for land use change emissions due to biofuels.

In their recent publication, Lark et al. have at least clearly confirmed that there is no evidence supporting deforestation and conversion of natural land to crop production due to biofuels or any other driver. Hence, from this perspective they confirmed the findings of other recent publications that there is no evidence of deforestation in the U.S. due biofuels.

However, Lark et al. simply assumed that RFS was responsible for an expansion in ethanol consumption by 5.5 Bgal a year. With this premise and by using a few loosely connected empirical methods, the authors evaluated the impact of the assumed increase in ethanol volume on three crops (corn, soybeans, and wheat). Relying on the short-term increases in the prices of these commodities during the time period of 2006-2010, assuming that these price increases will sustain over 30-year time period, projecting return on cropland and pasture land using problematic outdated projections for future crop prices and many other variables, applying CDL data with low accuracy in detecting land use types, ignoring the fact that reduction in CRP land area was due to CRP funding cut by Congress, Lark et al. projected the assumed increase in ethanol consumption by 5.5 Bgal would lead to an increase in corn area by 2.8 Mha over 30 year time horizon and that increases the area of active cropland by 2.1 Mha. Their projection suggested that most of the expansion in active crop land comes from conversion of one type of unused cropland (CRP) to crop production. Regardless of the accuracy of this projection with respect to the type of unused land and its magnitude, the fact that area of active cropland could increase by cultivation of unused land in the U.S. due to additional demand for biofuels is not new finding and has been addressed and well noted in the existing literature. However, the type of unused cropland that has been cultivated is uncertain. Finally, while the existing literature concludes that marginal cropland is not a rich soil carbon content land, Lark et al. assigned very high emissions factors to CRP land and concluded that emissions due to LUC for corn ethanol was large. In addition, in a misunderstood LCA practice, involving double counting and neglecting various sources of emissions savings due to biofuel production, Lark et al. maintained that the carbon intensity of corn ethanol is larger than that of petroleum gasoline.

As presented above, in this technical review of Lark et al., we address a few key and apparent issues that need more careful examination of Lark et al. We highlight these issues below:

- The Lark et al. modeling approach that followed only short-run changes in 2008-16 in individual crops - corn, soybeans, and wheat - missed the long-run pattern of changes in the mix of crops and the combined effect across all crops produced in the U.S. This short-term analysis generated a higher demand for active cropland and overestimated land conversion from CRP to crop production than what is consistent with observed trends in data.
- The arbitrary choice of working with CDL data for the short-time segment of 2008-16 does not represent the U.S. long-term cropping pattern. The farming sector in some years deviates from its long-term pattern in response to short-term shocks in commodity prices and then returns to its long-term pattern when short-term price shocks disappear.
- The Lark et al. modeling approach is too limited to effectively consider the drivers of ethanol industry and its interaction with other industries including the cropping and livestock industries. The Lark et al. modeling approach projected an increase in the planted area of corn by 2.8 Mha by considering one single factor of 5.5 Bgal ethanol in the U.S. For the same time period, due to all drivers, the average of annual changes in the harvested area for corn may have been -0.25 Mha in the U.S. What can justify the difference between the Lark et al. projection and actual observations? Are there some factors that canceled out the impacts of RFS2? Or has the modeling practice missed some important drivers?
- The RFS has begun in 2005, continued until today, and could be continued in future. Picking an arbitrary time segment out of this long time period can lead to distorted

results. Picking the time period of 2008-16 over which there was a major increase in crop prices (not only due to biofuels) and assigning the estimated land conversion for that period to a policy that will remain in place for a long time period can result in biased land use change attributable to the RFS. This biased attribution can certainly cause overestimated LUC magnitude for the RFS.

- The short-term changes in crop rotation does not reflect the long-run pattern of corn-soy rotation. Furthermore, Lark et al. with no justification picked a subset of their selected study regions to calculate changes in crop rotation. This selection eliminated areas with large shares in soybeans or wheat.
- Lark et al. did not recognized cropland pasture as a sub-category of cropland in their analyses and perhaps treated this type of land as pasture land or fallow land. This misidentification and the method used by them to assess land return artificially push the need for additional active cropland to CRP land.
- The CRP land left this program simply because there was no budget to keep them in the program. Assigning a portion expired CRP land to RFS (or any other biofuel) is problematic.
- To estimate probability of land transformation, Lark et al. used outdated and inaccurate projections for future crop prices and several other variables. In addition, in an ad hoc manner, they assumed costs of crop production remain constant over the 10-year projection period for the stream of expected returns on cropland. These made their land transformation projection questionable.
- We tested how much land expansion could be expected, given yield increases over the considered time frame as well as land offsets provided by DDG animal feed in order to meet the Lark et al. assumed 5.5 Bgal of ethanol stimulated by the RFS. Our analysis shows that at high level, yield increase on 2008 year corn acres over-compensate for ethanol demand. Even with ethanol production the 2008 corn footprint would still be down by 4.26 million acres. Ethanol demand may not drive an expansion above the 2008 year corn footprint but other factors including urban development may shift the corn footprint around.
- Our analysis of the cropland expansion data layer presented in Lark et al. supporting information revealed that areas identified by the authors as expansion to cropland may often be short-term fallow/idle lands (less than 10 years). In fact, many parcels identified by Lark et al in their "Cropland Expansion Layer" appear to be prime examples of land on the margin that is toggling between agriculture and fallow/idle state based on crop price signals. This would likely result in a systemic overestimation of SOC emissions for these parcels. Without such observation data to support their estimates, Lark et al. should have considered their results with high uncertainty.
- The authors missed the fact that corn ethanol LCA studies capture the N_2O emissions from any change in nitrogen applied to corn in farming GHG emissions. As a result, they may have double-counted N_2O emissions in their LUC emissions. They also failed to take

into account emissions savings due to avoided consumption and improvements in livestock industry induced by using biofuel by products.

- Lark et al. projected that in many counties area of cropland would increase largely (up to 2000 hectares for 1 hectare of changes in corn area). What justifies these magnificent changes? These large changes suggest that Lark et al. overestimated the land transformation elasticities.
- Lark et al. projected that the area of corn increases in 1,353 counties and decreases in 349 counties. In addition, their results showed changes in cropland in 126 counties with zero change in corn area. These odd results strongly suggest that the Lark et al. modeling approach may have considered reshuffles of crops among geographic locations of crop production with significant LUC emission implications.

References

Bigelow, D. and Borchers, A., 2017. Major uses of land in the United States, 2012 (No. 1476-2017-4340).

Copenhaver, K., Hamada, Y., Mueller, S. and Dunn, J.B., 2021. Examining the characteristics of the cropland data layer in the context of estimating land cover change. ISPRS International Journal of Geo-Information, 10(5), p.281.

Filip, O., Janda, K., Kristoufek, L. and Zilberman, D., 2019. Food versus fuel: An updated and expanded evidence. Energy Economics, 82, pp.152-166.

Lark, T.J., Hendricks, N.P., Smith, A., Pates, N., Spawn-Lee, S.A., Bougie, M., Booth, E.G., Kucharik, C.J. and Gibbs, H.K., 2022. Environmental outcomes of the US Renewable Fuel Standard. Proceedings of the National Academy of Sciences, 119(9), p.e2101084119.

Lusas, E.W., 2004. Soybean processing and utilization. Soybeans: improvement, production, and uses, 16, pp.949-1045.

Miao, R., Khanna, M. and Huang, H., 2016. Responsiveness of crop yield and acreage to prices and climate. American Journal of Agricultural Economics, 98(1), pp.191-211.

Pearson, R., Pritsolas, J., Copenhaver, K. and Mueller, S., 2020. Assessment of the National Resources Inventory (NRI), the census of agriculture, the Cropland Data Layer (CDL), and demand drivers for quantifying land cover/use change. The Energy Resources Center at the University of Illinois at Chicago.

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B.A.S., Schumacher, J. and Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone–carbon response functions as a model approach. Global change biology, 17(7), pp.2415-2427.

Ramcharan, A., Hengl, T., Nauman, T., Brungard, C., Waltman, S., Wills, S. and Thompson, J., 2018. Soil property and class maps of the conterminous US at 100 meter spatial resolution. Soil Science Society of America Journal, https://doi.org/10.2136/sssaj2017.04.0122.

Spawn, S.A., Lark, T.J. and Gibbs, H.K., 2019. Carbon emissions from cropland expansion in the United States. Environmental Research Letters, 14(4), p.045009.

USDA NASS. Quick Stats Database, https://quickstats.nass.usda.gov/.

Taheripour, F., Scott, D., Hurt, C.A. and Tyner, W.E., 2021. Technological progress in US agriculture: Implications for biofuel production. Sustainable Agriculture Research, 10(526-2021-498), pp.61-72.

Taheripour, F., Baumes, H. and Tyner W.E, 2022 Economic Impacts of the U.S. Renewable Fuel Standard: An *Ex-Post*. Evaluation. Frontiers in Energy Research, https://doi.org/10.3389/fenrg.2022.749738.

Wang, M., Wander, M., Mueller, S., Martin, N. and 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. Environmental Science & Policy, 129, pp.68-78.

Appendix A

S1. Key Assumptions, Approach, and Data for LUC Modeling in Lark et al.

a. A quick historical review of evolutions in U.S. harvested area

Lark et al. oversimplified the U.S. agricultural system, ignored interactions among crops, disregarded the connections between livestock and cropping activities, ignored the forward and backward links between agricultural and non-agricultural activities, and overlooked the long-term patterns in crop production. In a reduced form and simplified manner, the authors looked into short-term changes in corn, soybeans, and wheat markets to calculate LUC and their associated emissions due to the RFS. Here, we provide a short review of some long-term patterns in U.S. agriculture to highlight some of the omissions made by Lark et al.

Figure S1A shows the U.S. harvested area under two categories: primary crops and feed crops[4]. The first category includes all types of crops produced in the U.S., except forage and silage crops. The second category includes all types of forage and silage. This figure shows the harvested area of feed crops has declined gradually from 31 Mha in 1961 to about 25 Mha in recent years. Figure 1A shows that the area of primary crops increased from 89 Mha in the early 1960s to 118 Mha in the early 1980s, but then declined to about 100 Mha in 1990 and has fluctuated around that level since then. Figure 1A also shows the area of idled cropland signed up under CRP. It shows that the area under CRP has grown since the mid-1980s, when the harvested area of primary crops declined largely. The CRP area increased rapidly until 1990 to about 13-15 Mha, remained at that level until 2007, and then declined to about 9 Mha in recent years due to budget limitations. **It should be noted that CRP acreage is bound by statutory limits set by the Farm Bill and that the acreage limits for CRP were reduced from 13 Mha (32 million acres) in 2008 to 9.71 Mha (24 M acres) between 2010 and 2020.**

Figure S1B disaggregates the area of primary crops into three categories: corn and soybeans, wheat, and other primary crops. This figure shows three important trends. First, the area of corn and soybeans increased from 34 Mha in 1961 to about 58 Mha in the early 1980s. Then it dropped to about 50 Mha by the end of that decade. Since then, the area of corn and soybeans has followed a continuous increasing linear trend. Second, the area of wheat increased from 21 Mha in 1961 to about 33 Mha in 1981, and then continuously declined to 15 Mha. Third, the area of all other primary crops (including but not limited to rye, sorghum, barley, and oats) has declined continuously from 34 Mha in 1961 to 16 Mha in 2020. Figure 1B clearly shows that while the area of corn and soybeans has increased over time, the areas of wheat and many other primary crops have declined. The area of corn and soybeans increased by 17 Mha from 1990 to 2020, while the areas of wheat and other primary crops declined by 21 Mha. The long-term trend in the mix of crops produced in the U.S. began many years ago, before ethanol production or implementation of the RFS, and is not solely related to the short time period between 2008 and 2016, the time period that Lark et al. selected to study. **The Lark et al. modeling approach that**

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[4] In this note, we use official data sets that have been provided by the USDA data portals (e.g. NASS Quick Stats: USDA - National Agricultural Statistics Service - Quick Stats) or provided by the FAO at: FAOSTAT. It is important the FAO data and USDA match perfectly.

only followed short-term changes in individual crops—corn, soybeans, and wheat—overlooks the long-term changes in the mix of crops and the combined effect across all crops produced in the U.S. This omission has generated a higher demand for active cropland and overestimated land conversion from CRP to crop production than is consistent with observed trends in data.

Figure S1C disaggregates the total harvested area of corn and soybeans between these two crops. In 1961, the area of corn was 23 Mha and the area of soybeans was 11 Mha. Therefore, at that time, the area of corn was more than twice the area of soybeans. Then, the areas of both crops increased, with a much faster growth in the area of soybeans, to about 29 Mha at the end of 1970s. Since then, in some years, the area of corn is greater than that of soybeans, and in other years, the area of soybeans is greater than that of corn.

Figure S1D zooms in and highlights areas of production for these two crops since 1979. This figure clearly shows that the area of corn is greater than the area of soybeans in most years from 1980 to 1999. In early 2000s, the area of soybeans was larger than the area of corn. Then from 2007 to 2016, the area of corn was larger, and after that, the area of soybeans was again greater than that of corn. Lark et al. picked up the increases in corn area between 2008 and 2016 and project that the observed increases during this period would sustain for 30 years. Note that the availability of CDL data for this time period restricted the choice made by Lark et al. to this particular time period, which omits considerations of longer-term trends caused by factors unrelated to the RFS. **This biased choice does not match with the U.S.'s long-term cropping pattern. In some years, the farming sector deviates from its long-term pattern in response to short-term shocks in commodity prices and then returns to its long-term pattern when short-term price shocks disappear, as shown in Figure 1D.**

Figure S2A shows annual changes in the U.S. areas of corn, soybeans, wheat, and other primary crops from 2007 to 2016. This figure shows that corn area increased by 6.8 Mha in 2007, the year that RFS2 was approved, and that soybean area was reduced by 4.2 Mha. The following year, corn area declined by 3.2 Mha and soybean area increased by 4.3 Mha. In the rest of this time period, the areas of corn, soybeans, wheat, and other primary crops slightly fluctuated by about 1 or 2 Mha per year.

Figure S2B represent the average annual changes in the areas of corn, soybeans, wheat, and other primary crops for two time periods: 2007 to 2016 (covering 10 years) and the eight years targeted by Lark et al. This figure shows that from 2007 to 2016, the annual average areas of corn and soybeans increased by 0.65 Mha and 0.33 Mha, respectively, with a total reduction of 0.15 Mha in the area of wheat and other primary crops. The net average annual increase in the U.S. total harvested area of all primary crops for this period was just 0.83 Mha. For the eight years targeted by Lark et al. , the annual average changes in the area of corn and soybeans were -0.29 Mha and 0.9 Mha, respectively, and there was an annual average reduction of 0.24 Mha in the area of wheat and other primary crops. The overall increase in the annual average of U.S. total harvested area for this time period is just 0.37 Mha. The next section describes inconsistencies between these observations and the results published in Lark et al.

b. Inconsistencies of Lark et al. with historical trends

With no effort to determine the drivers of the observed expansion in the ethanol industry, Lark et al. attributed 5.5 Bgal of ethanol per year to the RFS between 2008 and 2016. The authors then projected an average annual increase of 2.8 Mha in corn area due to the assumed annual increase in ethanol over those eight years for a subset of U.S. agricultural area. Historical land use patterns do not support this projection. As shown in Figure S2B, the USDA data[5] show that U.S. harvested areas of corn declined by -0.29 Mha per year, on average, between 2008 and 2015 due to all drivers including the RFS and all other market forces (note that this is the same time period targeted by Larke et al.). Figure S2B also shows that total U.S. harvested areas of all primary crops (including a large number of crops in addition to corn, soybeans, and wheat) slightly increased by 0.37 Mha per year, on average, between 2008 and 2016, due to all drivers (and not only the RFS).

The difference between the projection made by Lark et al. and the actual observations of harvested area[6] suggests that Lark et al. probably missed many significant changes in U.S. crop production by applying a methodology that only examined changes in the area of active cropland due to changes in three crops (corn, soybeans, and wheat) and ignored changes in many other crops. It is also important to note that there are many factors that affect changes in commodity markets. Changes in ethanol market due to the RFS, non-RFS policies, or market forces are only a subset of these factors. In the real world, many of these factors interact and their interactions shape long-term LUC patterns. The Lark et al. modeling approach is too limited to capture these interactions and isolates the net effect of the RFS from many factors that play significant roles in shaping the long-term changes in U.S. agriculture. **When considering all drivers, the average annual change in the harvested area of corn between 2008 and 2016 was -0.25 Mha at the U.S. level, if a modeling practice projects an increase in the planted area of corn by 2.8 Mha due to just one driver (5.5 Bgal ethanol) in the same time period for a subregion of the whole U.S., then a critical question is: what can justify the difference? Are there some factors that canceled out the impacts of the RFS or has the modeling practice missed some important drivers (e.g., an ethanol tax credit, an increase in China's demand for corn, changes in gasoline price, and many other factors as explained in Taheripour et al. (2022))?**

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[5] Available at USDA - National Agricultural Statistics Service - Quick Stats)

[6] Note that since Lark et al. used CDL data, they could not assess changes in harvested area. Instead, they used planted area. However, as long as there is no major crop failure, the changes in harvested area and planted area should be similar.

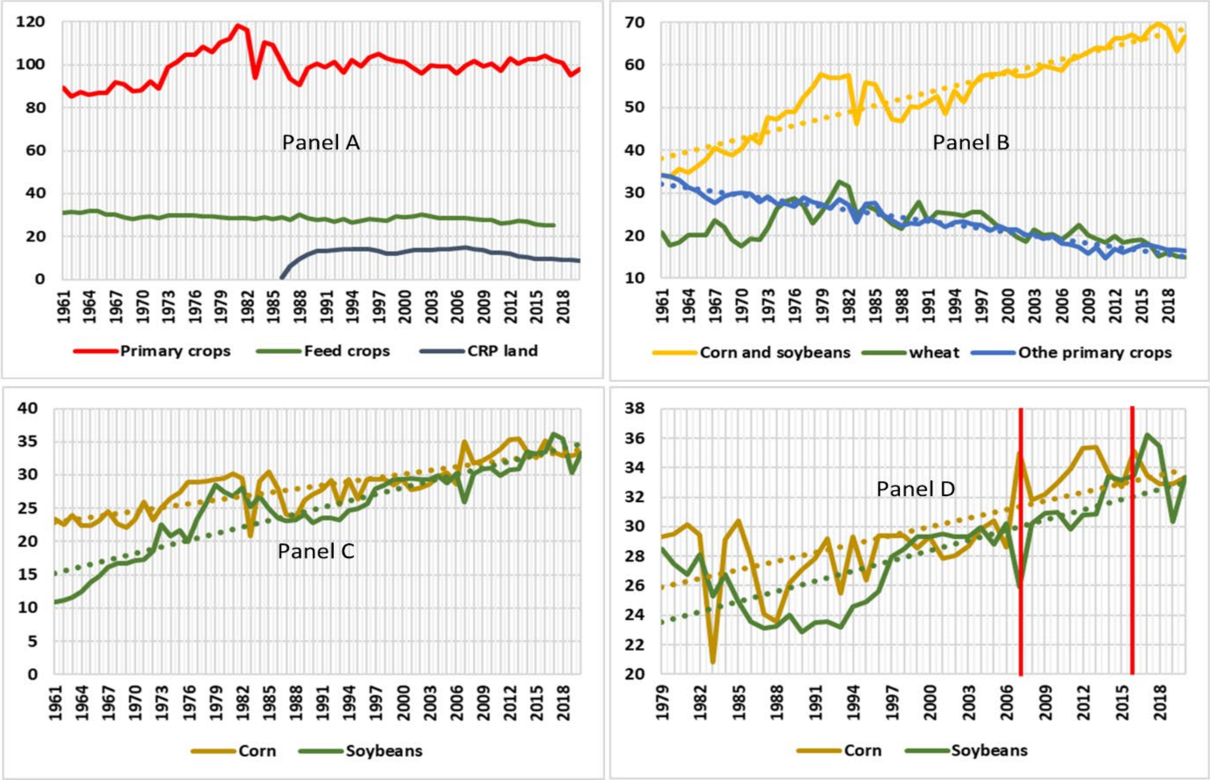

Figure S1. U.S. harvested area and the area of CRP land in million hectares from 1961 to 2020. Panel A represents areas of primary crops, feed crops (including forages and silages), and the CRP land. Panel B shows areas of the three primary crop categories: corn and soybeans, wheat, and other primary crops. Panel C shows areas of corn and soybeans separately. Panel D represents areas of corn and soybeans and their trendlines (highlighting the time period considered by Lark et al.).

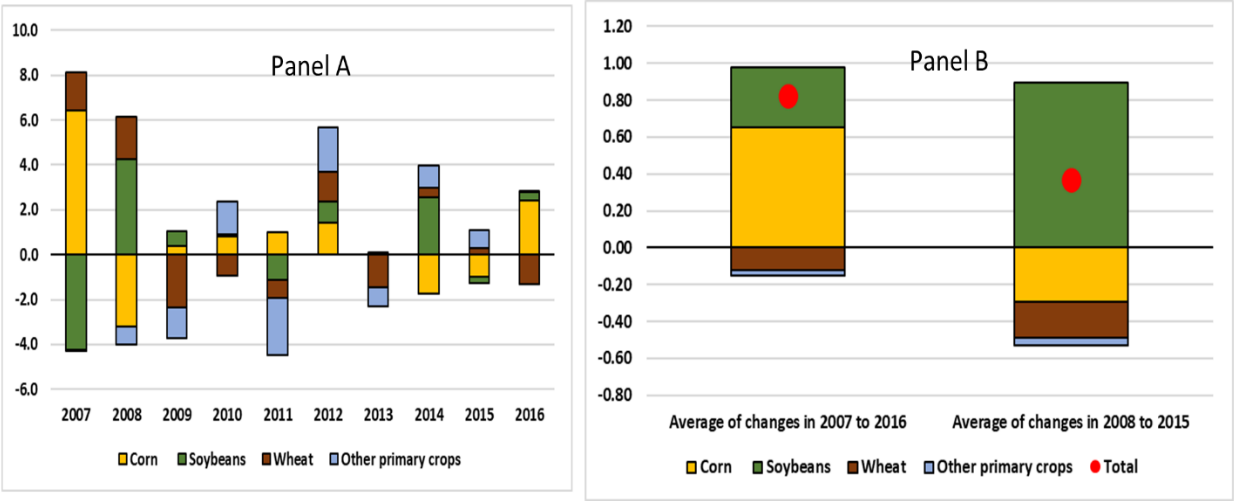

Figure S2. Annual changes in harvested areas for crops. The vertical axis of each panel shows area in million hectares. Panel A presents annual changes in the harvested areas of corn, soybeans, wheat, and other primary crops. Panel B show the average annual change by crop during two time periods.

c. Misattribution of industry impacts to the RFS

To assess the impacts of the RFS, Lark et al. attribute the assumed growth in the ethanol industry between 2008 and 2016 (5.5 Bgal/yr of added ethanol) to the policy, but neglect to assess the impacts associated with changes in production volumes of other renewable fuels governed by the policy (such as biodiesel, which increased by 0.88 Bgal/yr between 2008 and 2016). The increased fuel volumes of ethanol and biodiesel should have been evaluated together for RFS impacts. Furthermore, many additional factors contributed to the growth of the ethanol industry, which should have been separated from the RFS impacts.

The differences between the projection in Lark et al. and the recent land use trends may imply that the authors incorrectly specified the role of RFS and its interactions with many other biofuel policies and market forces that simultaneously shaped changes in U.S. crop production over time. Lark et al. assumed that the goals of the RFS on ethanol consumption are the only determinants of the expansion in ethanol industry between 2008 and 2016. **The expansion in the biofuel industry (including corn ethanol and other biofuels), even in the short time period between 2008 and 2015, occurred due to many drivers, including but not limited to changes in non-RFS biofuels supporting policies (such as elimination of Methyl Tert-Butyl Ether (MTBE) in gasoline blends biofuel tax credits), changes in crude oil price, changes in demand for gasoline, the 10% blend rule and the blend wall issue, changes in livestock industry and its demand for feed crops and other feeds (e.g., Dried Distillers Grains (DDG) and meal products), and perhaps the RFS. Lark et al. missed many of these factors.**

d. Significant ethanol volume increase happened right before 2008

The U.S. economy began to produce, consume, and trade ethanol prior to the approval of the RFS in 2005 and its amendment in 2007. The U.S. economy started to blend ethanol in the early 1980s. As shown in Figure S3A, the amount of ethanol blended with gasoline was about 1.7 Bgal at the beginning of the 2000s. The amount of ethanol blended with gasoline rapidly increased to 6.9 billion gallons in 2007, which was 47% higher than the mandated level of ethanol. The approval of the RFS in 2005 and its amendment in 2007 did not change the trend in ethanol consumption. The amount of blended ethanol continued to grow rapidly and reached12.9 Bgal in 2010.

The rapid growth in ethanol consumption prior to 2011 was due to an ethanol tax credit, a high crude oil price, ethanol's role in meeting oxygen requirements in gasoline after the elimination of MTBE in gasoline, a low corn price, and several other non-RFS policies. In fact, as shown in Figure S3A, from 2006 (the beginning of RFS1) to 2010, the amount of ethanol blended with gasoline was always higher than the RFS. In other words, during this time period, the RFS was not binding. In this time period, the Renewable Identification Numbers (RINs) prices were close to zero, for details see Taheripour et al. (2022). The rapid growth in ethanol consumption (and production) suddenly disappeared in 2011. The elimination of the ethanol tax credit, a sharp increase in corn price, a reduction in crop oil price (and gasoline price), reaching the ethanol blend wall of 10%, and several other factors jointly halted the rapid growth in ethanol consumption in 2011. Since then, ethanol consumption continued to grow slowly and increased from 12.9 Bgal in 2011 to 14 billion gallon in 2015, and has remained around that since.

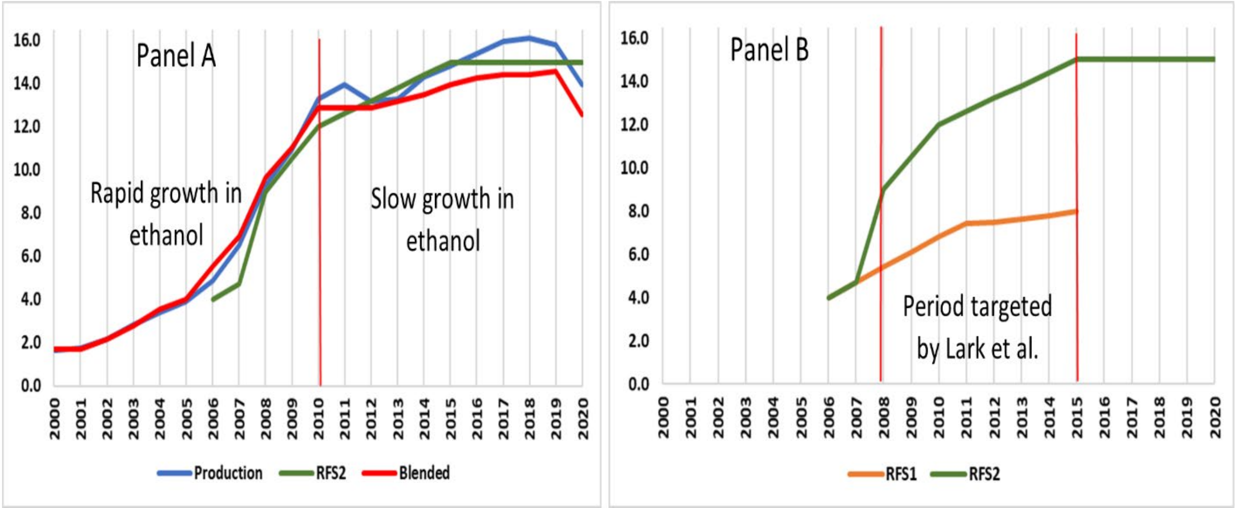

Figure S3. Production, consumption, and the annual RFS target for corn ethanol. The vertical axis of each panel shows the amount of ethanol in billion gallons.

e. *Stabilization and reversion of land conversion (especially in corn and soybean areas) after 2016*

Lark et al. picked the short time period from 2008 to 2015, simply considered the difference between the goals of RFS1 and RFS2 as the impact of the ethanol mandate, and used a chain of loosely connected empirical models to estimate changes in crop rotation and the conversion of non-cropland to cropland without showing the validation of their results by comparing them to actual observations. Then, the authors assumed their estimated changes would be sustained for 30 years of the ethanol mandate, as noted on page 3 of their main manuscript: "*Assuming 30-y amortization, ecosystem C emissions from the RFS induced LUC*." This is a biased approach for several reasons.

First, it is important to note that farmers' short-term responses to changes in crop prices often differ from their long-term responses. Figure S4 shows the ratio of corn to soybeans planted area in six large corn producing states from 2000 to 2020. This figure clearly shows that the ratio of corn to soybeans areas followed an increasing trend from 2000 to 2007, declined sharply in 2008, continued to grow from 2012 to 2014, and then declined until 2020. The sharp increase in the ratio of corn to soybeans areas in 2019 is due to the Chinese tariff on soybeans in this year. Figure S4 shows that the corn-soy rotation changed in favor of soybean from 2012 or 2013 to 2020. **Picking short-term changes in crop rotation and extrapolating those into a future period for the next 30 years is not empirically justified.** Additionally, the price effects induced by the RFS have varied over time. Other studies, such as Filip et al. (2017), show that the transmission of price effects is not smooth. These authors show that the relationship between fuel and food prices followed different patterns within three different time periods: November 2003 to June 2008 (prior to the food price crisis), July 2008 to February 2011 (during the food price crisis), and March 2011 to May 2016 (after the food price crisis). Although biofuel prices were affected by food crop and fuel prices in all periods and in all three regions, biofuel prices had the greatest impact on food crop prices during the food crisis period.

Second, the RFS time horizon is not limited to the time horizon picked by Lark et al. The RFS was in place before 2008 and after 2015. The RFS began in 2005, continues to today, and could be continued in future. **Picking an arbitrary time segment out of this long time period can lead to biased analyses.** Note that the availability of CDL data for this time period restricted the choice of Lark et al. to this biased time period.

Third, the time period selected by Lark et al. represents a period where crop prices rose sharply in the U.S. and across the world. Figure S5A shows that crop prices reached their peak in the time period selected by Lark et al. and then decreased rapidly after that time period. Figure 5B shows the same story at the global level for aggregated food and crop prices. Figure 5A clearly shows that before and after the time period selected by Lark et al. crop prices were lower significantly. **Picking the time period from 2008 to 2016 over which there was a major increase in crop prices and assigning land conversion to crops during the period to a policy that remained in place for a long-time results in biased LUC attributable to the RFS. This biased attribution certainly overestimates ethanol volume and LUC magnitude for the RFS.**

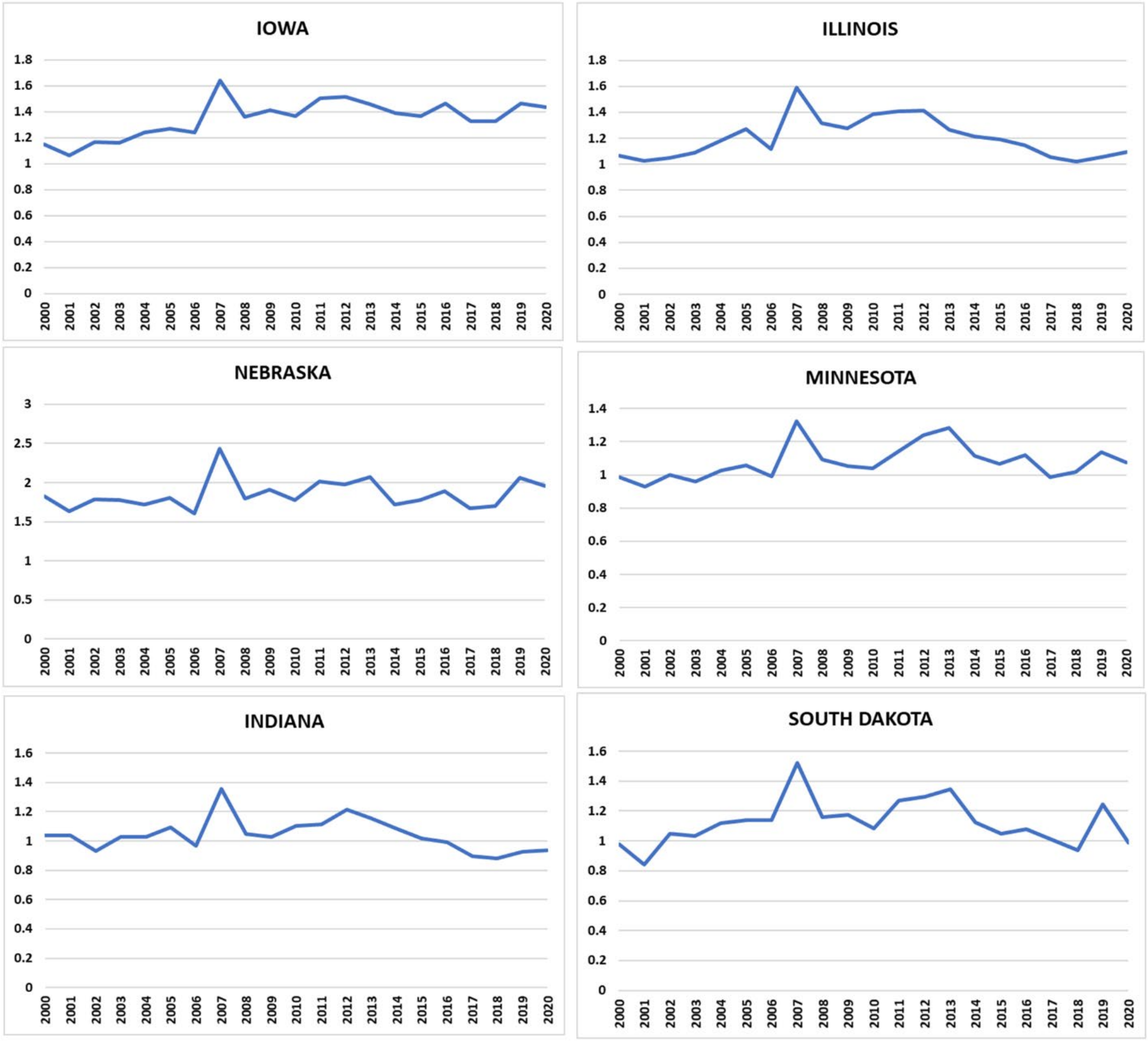

Figure S4. The ratio of the area of corn to the area of soybeans in six states.

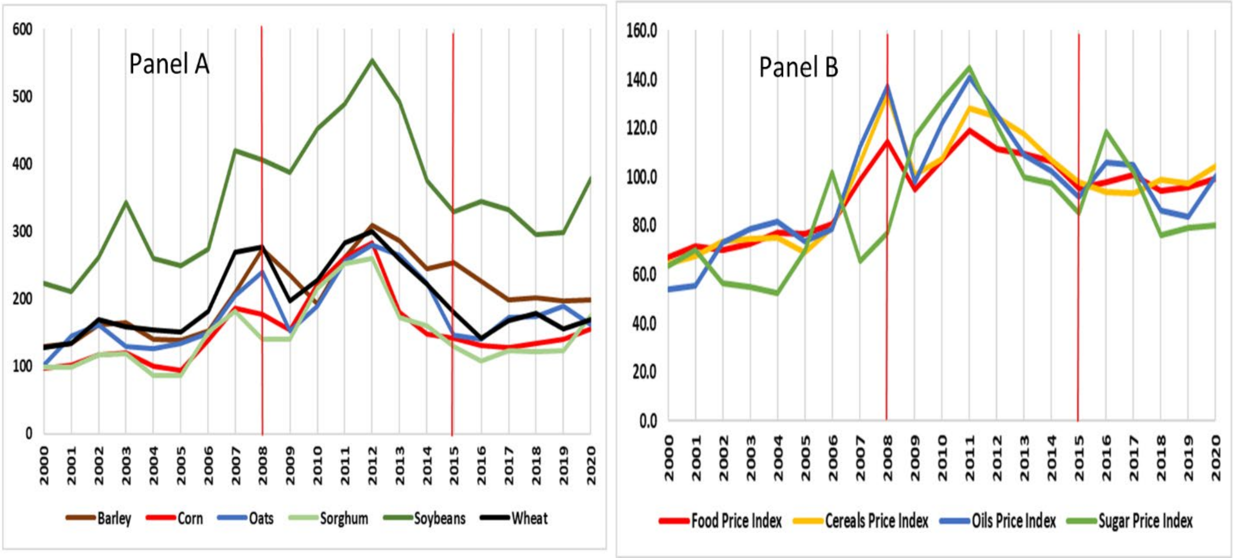

Figure S5. Global price changes of crops. The vertical axis of panel A shows real crop prices in $ per metric ton. The vertical axis of panel B shows price index in percent at the global scale.

S2. Modeling of LUC with Econometric Modeling

Estimation of biofuels LUC is a complicated issue to address causality of LUC from increased biofuels production. Over the past 15 years, economic models have been used to address causality with economic linkages among different activities within the agricultural sector and between it and other sectors. Lark et al. dismissed all the complications and turned the whole U.S. agriculture and its related industries into three crops (corn, soybeans, and wheat), and even dismissed interactions between these crops from both the supply and demand side.

U.S. agriculture and its related industries include a large number of producers, traders, and research entities that supply food products for a large portion of the world population. The U.S. agricultural industry does not only produce corn, soybeans, and wheat, but also many other crops in large areas, especially when compared to total arable land areas of many other countries. Crop producers in the U.S. are in close connection with the livestock industry that demands feed items. Many crop producers in the U.S. are livestock producers as well. The U.S. agricultural sector not only supplies corn to the ethanol industry, but also produces DDG, a feed item for animal production. It is questionable to assume a one-way mechanical relationship between the corn and ethanol industry and ignore the overall interactions between the U.S. agriculture and biofuel industries, including the ethanol industry. In fact, changes in the demand for meat products are major drivers of changes in the demand for feed items. The transition in demand for meat from beef to pork and poultry has altered the demand for land and feed items in the livestock industry. **The livestock industry's demand for land and feed crops has shifted toward processed feeds, such as meals and DDG, which are the outputs of producing biofuels. The livestock industry's demand for these feed items has a significant effect on the growth of the biofuel industry. Lark et al. have overlooked these facts.**

U.S. farmers plan and produce crops based on long-term views, while managing short-term changes in economic and non-economic conditions. The U.S. agricultural industry has strong forward and backward linkages among food, feed, and biofuel industries. The US agricultural industry is a point of connection for many other industrial and service activities.

The Lark et al. modeling approach ignored all of these activities, connections, and links, simplified the U.S. agricultural system into three crops, estimated a few lands transition functions, and assessed the land use implications of the RFS based on their estimated functions. As we commented earlier in this note (see section 1.d), Lark et al. also oversimplified the policy in an environmentally inappropriate way for RFS-induced LUC. The U.S. policy towards biofuels has several layers and components. Over time, various policies or incentives at federal, state, and local levels have been implemented to encourage the production of biofuels. Prior to the approval of RFS1 in 2005 and RFS2 in 2007, the non-RFS policies, in particular the biofuels tax credit policy, have made significant interests in investment in the biofuel industry.

Lark et al. have paid no attention to these facts and simply assumed that the differences between the annual goals of RFS1 and RFS2 from 2008 to 2016 represent the effects of the RFS on the ethanol market and calculated LUC due to that. The Lark et al. approach is too limited and biased to provide a credible estimate for induced LUC due to the RFS policy.

With the above general considerations, we address some critical points regarding the approach used by Lark et al. to assess land use impacts of the RFS below.

Assessment of RFS price impacts: Lark et al. used VAR approach and assessed the price impacts of an increase in ethanol demand by 5.5 Bgal, and inappropriately assigned that to the RFS, as explained in the previous section. Beginning with that misspecification, here we address some important points about the estimated price impacts of the RFS.

Lark et al. noted: "*Our model incorporates the fact that the RFS is a persistent rather than 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 uses data on inventory levels and on the term structure of futures prices.*"

Regarding the first statement in the above paragraph, non-RFS polices and market forces, not the RFS, drove the expansion in ethanol industry prior to 2011, as explained earlier in this note. Second, if the authors think that the RFS is "*a persistent rather than transitory shock to agriculture*," they should not have limited their analysis to 2008 to 2015, since the RFS has been in place since 2005 until today (2022). Third, it is true that changes in inventory are transitory remedies to partially absorbed price shocks, but that is not the only transitory remedy. Short-term changes in crop rotations are also transitory actions, as frequently implemented by farmers in practice. As explained in section 1.e of this note, actual data confirms short-term changes in crop rotation in favor of corn, but after one or two years farmers returned back to their long-term rotations.

Changes in corn rotations: Lark et al. estimated two sets of equations: the probability of planting corn in time t and t-1 on the same field and the probability of planting corn in time t on a field that was planted in t-1 for other crops. It seems like these probability functions were estimated using a "sample included 3.6 million fields that accounted for 91.6% of corn area between 2009-16, inclusive." Then the authors used the two sets of estimated functions to assess the impacts of the RFS (the assumed increase in corn ethanol by 5.5 Bgal) on the following rotations: corn on corn, other on other, and corn on other. To accomplish this task, Lark et al. "assumed an estimated 30% persistent increase in the price of corn and 20% increase in the prices of soybeans and wheat." The approach followed by these authors represents various selection biases.

First, the sample period is biased, as describe above in detail. Second, Lark et al. followed a biased process within their selected time period. Their SI noted that: "We estimated the models for all fields greater than 6 ha (15 acres) that were in regions where (i) over 20% of the total area was cropland; (ii) more than 10% of cropland area was planted to corn; and (iii) more 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 were available to train the model."

This set of criteria eliminates a large portion of the total planted area of the U.S. In particular, the second restriction eliminates fields that were soybean, other crops, or their total area had a share more than 10% in planted area. What is the justification for imposing this biased restriction? Lark et al. noted that their selected area covers 91.6 million acres of corn area, but they did not mention what portion of total planted area (or soybean area) has been eliminated.

Third, as mentioned in the previous section, the price estimates of a 30% increase for corn and a 20% increase for soybean and wheat are biased, therefore their impacts on crop rotations are biased as well.

***Modeling land transition*:** To assess LUC due to 5.5 Bgal assigned to the RFS, Lark et al. assessed two classes of land conversions:

1) Expansion in cropland from pasture land and reverse,

2) expansion in cropland from CRP land and reverse.

This classification in land transformation omits some complicated issues in land transformation. While we can have an extended discussion on land classifications and definitions from a standard point of view defined by the IPCC, to avoid complication in this short note, we introduce one more land type according to the U.S. Agricultural Census "cropland pasture".

The area of cropland, ignoring fallow land, is a composite of:

i. Active cropland: cropland under crop production,
ii. Land under CRP: land that was under crop production for a long time in the past and is currently under conservation practices, usually for a short time period (10 to 15 years),

iii. Cropland pasture: another type of cropland that was cultivated for crop production in the past but remained uncultivated for a few years. This is different from fallow land, as fallow land remains idle with no use by livestock.

In general, CRP land and cropland pasture are both marginal croplands[1]. When commodity markets are bad and crop prices are low, these marginal lands go out of production. When marginal croplands are out of production, they may sign in the CRP, if they pass some required environmental threshold, and if a CRP signup is available. Otherwise, they remain fallow or can be used as “cropland pasture” or transferred for another use. When commodity markets recover, cropland pasture could return to production with no limit, but CRP land should wait until the end of the CRP contract.

As mentioned in this note, the CRP area has increased rapidly from zero to about 13-15 Mha in the late 1980s, remained at that level until 2007, and then declined to about 9 Mha in recent years. The area of cropland pasture was about 26.3 Mha in the late 1980s and remained around that level until the late 1990s. It then dropped to 5.5 Mha in the latest US agricultural census in 2017. A portion of the recent reduction in the area of cropland pasture could be due to transitions to active cropland, pasture land, and non-agricultural uses. As reported by Bigelow and Borchers (2017), a portion of the observed reduction in the area of cropland pasture in recent years could be due to a recent change in the definition of the cropland pasture category.

Satellite data cannot distinguish whether land is CRP or cropland pasture. With additional information one could approximately (with some errors) detect these lands, as Larke et al. did for CRP land, with additional information obtained from the CRP signup information.

However, Lark et al. did not recognize cropland pasture as a sub-category of cropland in their analyses and perhaps treated this type of land as pasture land or fallow. This misidentification and the method used by these authors to assess land return artificially push the need for additional active cropland to CRP land, as explained below.

To satisfy the additional demand for active cropland, Larke et. considered two sources: CRP and pasture land. Their results shows that CRP has a large share in the land conversion. However, there are, in fact, three choices to increase active cropland:

iv. Conversion of CRP land to active cropland,
v. Conversion of cropland pasture to active cropland,
vi. Conversion of pasture land to active cropland,

Now consider now the choice between CRP and cropland pasture. If CRP is still under contract, that land will not be a choice to be transferred to cropland. If the CRP land is out of contract, then the choices are converting the CRP land with no contract, converting available cropland pasture, or converting a portion of each. Then the choice between pasture land and the bundle of “CRP-cropland pasture” will depend on their expected returns.

Considering cropland pasture as a part of pasture land (or fallow land) in the land transformation function is a misleading practice, as the return on cropland pasture when returned to cropland will be similar to CRP and much higher than the return on converting pasture land.

Regardless of the above misidentification, it is important to note that, if a CRP contract has been expired, the land will go outside of the program anyway. The CRP program has been under restriction with major caps on new enrolment since 2007. Between 2008 and 2015 (the years targeted in Lark et al.), the area of CRP has declined by more than 5.1 Mha across the U.S. (more than 4 Mha in the area targeted in Lark et al.). The reduction in CRP land was not due to the RFS or any other driver. **The CRP land left the program simply because there was no budget to keep it in the program. Assigning a portion of expired CRP land to the RFS (or any other biofuel) is baseless.**

The observed reduction of 5.1 Mha in CRP land was not a choice made by the crop producers. It was enforced by budget cost (USDA, 2021). Farmers have no commitment to keep their land out of production if there is no budget to do so. Carbon losses (if there are any) from converting CRP lands with expired contracts to crop production (or any other uses) may be attributed to the policy that limited the CRP program, but not to the RFS. Farmers are better off keeping their land under CRP if they paid for it and converting their cropland pasture and fallow land to crop production.

To estimate the probability of land transformation, Lark et al. have used some available data generated by USDA. For example, they noted that: "*We constructed cropland returns as a 10-year discounted stream of expected returns averaged across the relevant crops of the county, assuming a discount rate of 5%. ... Projected prices for the next 10 years were obtained from the Agricultural Baseline Database from the Economic Research Service.*"

Each year USDA projects crop prices (e.g., corn) for the next 10 years. For example, in 2000, USDA projected that the farm price of corn (measured in $ per bushel) would be 1.8 in 1999-2000, 1.85 in 2000- 2001, 1.95 in 2001-02, …, 2.40 in 2004-2005, …, and 3.10 in 20092010.

We denote USDA's projected prices of corn for the year of report with PY0, for 5 years in the future with PY5, and for 10 years in the future with PY10. Table 2 shows the deviations between the USDA projections with actual realizations of annual corn prices for the report years from 2000 to 2015. For example, the 2004 USDA report projected that the corn price would be 2.1, 2.3, and 2.35 $ per bushel in the years of 2003/2004, 2008/2009, and 2013/2014, respectively. The realization of corn prices for those years were about 2.06, 3.56, 3.71 $ per bushel. Hence, as shown in Table 2, the errors in the 2004 USDA reports for the future projections of 2003/2004, 2008/2009, and 2013/2014 were about 2%, -35.3%, and -36.6%. In general, Table 2 shows that the USDA reports badly underestimated the future corn prices. **Lark et al. relied on many of these types of projections to establish returns on cropland in their estimation process for land transformation probabilities.**

As also explained in their SI, Lark et al. followed many simplifying assumptions when they were faced with data limitations. As an example, consider the following assumption made by Lark et al: ***"For all categories, we assumed costs remain constant over the 10-year projection period for the stream of expected returns."*** What could justify this assumption? On the one hand, these authors used under estimated projections for crop prices with huge errors. On the other hand, they assumed that costs of producing crops are constant over a 10-yr time horizon.

When Lark et al. plugged crop prices into their estimated probability functions to calculate land conversion, they used the average values of the largest observed changes in crop prices (a 30% increase in corn price and 20% increases for soybeans and wheat prices) and assumed no increase in the costs of crop production. This is an invalid and biased approach.

The issues with the Lark et al LUC assessments are not limited to the above cases. First of all, they estimated the probability of expansion in cropland area for many NRI points at the county level without revealing their estimated parameters for each function. What valid statistical tests were used? How many of the estimated parameters are statistically significant and how many of them are insignificant?

The SI says: “We estimated the area of land that transitioned to and from cropland 2009-16, inclusive, for each region due to the RFS. For transitions with pasture, we first predicted the probability of transitions at each point with observed crop returns between 2009-12." Why 2009-2016 and not 2008-2016? Why are returns included for the time period 2009-2012 and not for 2009-2016. What justifies the selection of these inconsistent time segments?

Using the estimated probability functions, the estimated returns, and some local control variables LUC was estimated for NRI points (or counties). What aggregation or disaggregation process was used to meet the target for 5.5 Bgal of ethanol?

Table S1: Percent errors in USDA projections for corn price

Year of projection	Projection for:		
	PY0	PY5	PY10
2000	-2.9	19.6	-40.2
2001	-6.6	-26.2	-58.2
2002	-9.2	-45.1	-62.2
2003	-0.5	-45.9	-46.3
2004	2.1	-35.3	-36.6
2005	-5.3	-53.7	-32.1
2006	-40.9	-58.2	-22.5
2007	-28.4	-49.2	-1.6
2008	-13.9	-21.7	-0.2
2009	23.7	-1.6	-2.2
2010	-31.5	2.6	-15.0
2011	-16.4	22.3	*
2012	-2.7	34.2	*
2013	70.0	24.8	*
2014	21.3	-6.1	*
2015	-3.0	-17.3	*

* Price realization does not exist yet.

[1] Some CRP lands may not necessarily be marginal land.