Food and Agricultural Policy Research Institute
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Literature Review of Estimated Market Effects of U.S. Corn Starch Ethanol

February 2016

FAPRI-MU Report #01-16

Prepared by the Food and Agricultural Policy Research Institute, Division of Applied Social Sciences
University of Missouri

www.fapri.missouri.edu

Published by the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri (MU), 101 Park DeVille Drive, Suite E; Columbia, MO 65203. FAPRI–MU is part of the Division of Applied Social Sciences (DASS) in the College of Agriculture, Food and Natural Resources (CAFNR).

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This material is based upon work supported by the U.S. Department of Agriculture, under Agreement Nos. 58-0111-15-008 and 58-0111-15-021.

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Any remaining errors are those of the authors.

Summary

This report reviews published estimates of how corn starch ethanol affects markets. This review was developed by staff at the Office of the Chief Economist of the U.S. Department of Agriculture and FAPRI-MU with a view to provide an objective assessment of recently published scientific findings. We review literature published from 2010 to 2015 related to the impact of corn starch ethanol on corn price and quantity, land use, livestock, and liquid fuels.

This information can help to assess some of the consequences of biofuel quantity changes and can be used to support GHG emission calculations. Focusing on recent studies is intended to make the results relevant to the current market and policy environment.

The task to make judgments about how to use published estimates of over 170 studies and compare these disparate studies is fraught. We might misunderstand some studies and misuse their results. We might make mistakes when we convert numbers into comparable measures.

Key results

- The median *US corn price* impact is 0.15 dollars per bushel increase from a billion gallons of additional corn starch ethanol, excluding short-run price impacts. The corn price effect tends to be higher for studies without supply response, particularly one-year studies during the drought, and for smaller changes in corn starch ethanol or smaller corn starch ethanol levels overall.

- *Corn production* effect suggests that well under half of the increase in corn demand to make the additional ethanol is met with greater production, even giving time for supply to respond. Some studies estimate that the production increase offsets the increase in demand, but most do not.

- *Land use* estimates vary. Some studies imply that a dollar higher corn price can lead to millions of more acres allocated to corn or other crops in the US and elsewhere in the world, some drawn from forest area. Some studies focus on short-run response with limited or no land use change. There are few observations and the range of estimates is sometimes quite wide.

- The impacts on *livestock*, *liquid fuels*, and *crop yields* are not often reported. However, these limited results support the expected effects of an additional billion gallons of corn starch ethanol: rising livestock prices and lower livestock quantities; and falling US gasoline use due to competition with ethanol and higher fuel costs, plus a partly offsetting rise in rest of world gasoline use.

Studies do not always state that certain factors are explicitly represented. We are unable to draw strong conclusions about the effects of corn starch ethanol co-products (distillers grains, corn oil), ethanol trade, the possibility that the mandate is not binding, or compliance costs.

Direct application to RFS analysis might cause errors. First, scale, starting values, and time frame affect results. Second, many studies omit potentially important market or policy factors, like co-products or compliance costs. Third, many studies assume the RFS is binding without regard to interactions within the mandate hierarchy and complications of non-binding RFS components.

Table 1. The impacts of one billion gallons of corn starch ethanol, median values.

One billion gallons more corn starch ethanol is associated with changes in…	**Number of observations**	**Median value**
Corn price		dollars per bushel
Focused studies, with supply response	26	0.15
Focused studies, with or without supply response	36	0.19
Focused studies, big changes (>5 b.g.)	10	0.07
Focused studies, big levels (>15 b.g.)	8	0.12
All studies with sufficient information	66	0.13
All refereed articles with sufficient information	23	0.04
Corn production		billion bushels
Focused studies, with supply response	8	0.12
Focused studies, with or without supply response	18	0.00
All studies with sufficient information	35	0.11
All refereed articles with sufficient information	11	0.13
Livestock and milk prices (using focused studies only)		dollars per ton
Beef	6	3.79
Pork	6	3.98
Poultry	6	3.94
Milk	2	4.29
Gasoline use in the US		billion gallons
Focused studies, with supply response	9	-0.8
All studies with sufficient information	23	-0.9
All refereed articles with sufficient information	8	-1.0
Gasoline use in the rest of the world		
Focused studies, with supply response	5	0.5
All studies with sufficient information	8	0.5
All refereed articles with sufficient information	7	0.5

Notes: "focused studies" refers to studies whose market effects can be traced to a change in US corn starch ethanol quantity only; results of all studies with sufficient information might be affected by complications such as changes in other policies in the US or other countries; details behind these calculations, including challenges and key definitions, are provided in the subsequent text; and the median values provided here are the middle values of ranges that vary widely in some cases.

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Goal of the literature review

We survey the results of recent studies that estimate the changes in agricultural commodity markets or greenhouse gas (GHG) emissions from additional US corn starch ethanol driven by the Renewable Fuel Standard (RFS). Together, staff at OCE/USDA and FAPRI-MU decided to target scientific estimates of or relating closely to US corn starch ethanol GHG emissions published from 2010 to 2015 as our focus.

The EPA's Regulatory Impact Assessment (RIA) published in 2010 was a large-scale review of information available at that time. Our goal is to assess recent impacts since then, not to evaluate studies before 2010.

OCE/USDA and FAPRI-MU staff adopted as the goal an objective assessment of key indicators of the economic impacts of ethanol. Economic links can be measured by such indicators as the impacts on corn price and production, land allocation, livestock product output and prices, and fuel market quantities.

We compare studies using key ratios of effects. This approach (a) focuses on the economic relationships that drive indirect effects associated with corn starch ethanol expansion, (b) allows us to include many studies, and (c) avoids qualitative and subjective assessments as much as possible.

We collect other facts about studies, such as method used, dates of publication and data, and whether or not other product and co-product markets are explicitly represented. This information helps us to understand what factors tend not to be well studied and to look for explanations for any systematic differences in estimated effects among reviewed studies.

The technical aspects of GHG emissions tied to specific activities are not the focus of this literature review. We do not review studies that estimate exactly how many GHGs are emitted by land use change, converting corn to ethanol and co-products, producing and applying fertilizer, burning different fuels in different vehicles, or any number of other considerations. One use of the ratios we produce would be to link them to technical parameters reflecting GHG emissions associated with the market impacts of U.S. corn starch ethanol, but we do not do so in this study.

Method

There are several steps between a change in the RFS and changes in GHG emissions and there are several paths to trace out when identifying how RFS changes can cause GHG emissions. We disaggregate GHG emissions into the volumes associated with agriculture, other biofuels, and petroleum products. Agricultural GHG impacts can be decomposed further into the sum of emissions associated with yields, area, and livestock.[1]

We try to extract from as many studies as possible key waypoints in the steps from RFS changes and corn starch ethanol use to the final agricultural and liquid fuel market impacts. We use ratios that indicate the size of the impact at certain points:

the change in corn starch ethanol quantity caused by a change in the RFS;

[1] We assume the reader is familiar with terms that we use throughout this report, such as corn starch ethanol, binding or non-binding mandates, and RFS compliance costs. These terms are explained elsewhere (see Thompson, Meyer, and Westhoff, "The New Markets for Renewable Identification Numbers" *AEPP*, 2010; Thompson, Meyer, and Westhoff, "What to Conclude about Biofuel Mandates from Evolving Prices for Renewable Identification Numbers?" *AJAE*, 2011; and Meyer and Thompson, "US Biofuel Baseline Briefing Book" FAPRI-MU 04-10, 2010.) and used in other publications.

the change in corn price caused by the change in corn starch ethanol quantity;
the changes in crop yields caused by the change in corn price;
the changes in land use caused by the change in corn price;
the changes in livestock quantities caused by the change in corn price; and
the changes in quantity of other liquid fuels caused by the change in ethanol production.

These ratios embed many interactions. For example, the corn price change causes other changes, and the combined impact will influence land uses and livestock numbers. We reduce these complications into a small set of parameters.

There is ample room for error. Published work is often curt, providing little or insufficient information about key effects. In many cases, we make judgments about how to use the raw material of various studies in order to make the numbers applicable in our framework.

Another challenge is that the necessary data are not always available. We often turn to nearby ratios that provide relevant information. For example, the ratio of the change in corn production to the change in corn starch ethanol indicates corn supply response. This ratio supplements area ratios and is particularly useful because we do not often see explicit yield impacts. Another example is the ratio of livestock price change, not just quantity change, as an additional indicator of livestock market impacts.

Overview of studies used

We read over 170 studies focused on corn starch ethanol, RFS, or related topics that were published in 2010-2015 (Table 2). Coverage for 2015 is partial: our review might not capture a large share of the studies published late in the year. The distribution of studies among other years varies somewhat, but not widely.

About two-thirds of the studies are refereed journal articles. Research reports and proceedings papers make most of the other third.

General equilibrium models are a popular tool for this sort of work, and GTAP has proven particularly successful. Partial equilibrium models drive about half as many of the studies. Other methods include literature reviews, statistical methods, and calculations based on processes.

It is often difficult to determine with confidence what goes into a study. Model details are necessarily limited for journal articles and most other outlets. We noted characteristics of models when we had a reasonable confidence that it was present, but there are almost certainly some studies that include one or another effect without explicitly saying as much. The numbers in the table that tally the models with specific characteristics likely understate the real levels.

Excluding literature reviews, less than a third of all studies clearly included distillers grains, livestock, fuel markets, or compliance costs, and only slightly more included ethanol trade. A larger share assumed that the RFS is binding.

Table 2. Summary of studies that were reviewed.

	Number	Share of total or subtotal		Number	Share of subtotal
Total number of studies	173	100%			
			Studies focused on biofuels more generally		
			total	86	100%
Publication date			**of which, those that explicitly include**		
2010	31	18%	distillers grains	34	40%
2011	32	18%	livestock	37	43%
2012	31	18%	ethanol trade	48	56%
2013	40	23%	fuel markets	37	43%
2014	27	16%	RFS compliance costs	11	13%
2015	12	7%	assumed binding RFS	50	58%
			year of estimated impacts		
Outlet			before 2010	14	16%
refereed journal	112	65%	2010-2015	21	24%
other	61	35%	after 2015	34	40%
			other or not specified	17	20%
Approach					
literature reviews	19	11%			
general equilibrium	65	38%			
partial equilibrium	34	20%	**Studies focused on corn starch ethanol**		
other	55	32%	total	41	100%
			of which, those that explicitly include		
Studies excluding literature reviews,			distillers grains	14	34%
total	154	100%	livestock	12	29%
of which, those that explicitly include			ethanol trade	17	41%
distillers grains	47	31%	**year of estimated impacts**		
livestock	48	31%	before 2010	12	29%
ethanol trade	60	39%	2010-2015	14	34%
fuel markets	48	31%	after 2015	7	17%
RFS compliance costs	14	9%	other or not specified	8	20%
assumed binding RFS	64	42%			

For most of this literature review, we restrict our focus exclusively to studies that relate to biofuel impacts in general or even to those that focus on US corn starch ethanol. Consider these two examples: one study estimates what happens if the US RFS changes in such a way that additional corn starch ethanol must be used, and there is no other driving factor; and a second study estimates what happens if there are broad changes to the RFS that cause greater corn ethanol, advanced biofuel, biodiesel, and cellulosic production. In the former case, we can be more certain that corn ethanol is the source of the estimated market impacts. In the latter case, changes in prices and quantities of agricultural commodities and land use might actually have little to do with corn ethanol. About half the studies generate quantitative estimates that relate to biofuels and include corn starch ethanol, so could be useful. About a quarter of all studies appear to relate directly to the impacts of corn starch ethanol.

The shares of studies that clearly include some of the complexities of these markets rise if we focus only on studies that seem more relevant. However, the inclusion of many characteristics remains below 50% and more than half assume the RFS is binding. Only 13% are believed to include mandate compliance costs.

Many studies do not need to include all these characteristics. Many studies focus on one particular question and do not need to entertain other complications. If authors want to see how corn starch ethanol affects land use, then fuel markets might not be directly relevant. A study of the impact of ethanol on fuel markets probably does not have to have distillers grains explicitly represented. However, if a study is intended to generate comprehensive estimates of price effects, welfare impacts, or lifecycle GHG emissions relating to corn starch ethanol, then we might expect a broad treatment that attempts to include the various impacts of the biofuel and co-products.

The data period relating to the estimated effects is perhaps more important than the publication date. The share of studies that look ahead, if judged as of early 2016, is two-fifths if looking at studies that estimate the impacts of corn starch ethanol or broader changes and less than a fifth of studies that focus on corn starch ethanol. Approximately half of the studies that are likely to be relevant focus on a time period that represent conditions before 2016. For example, studies of market conditions in 2012, at a time of drought and low crop yields, were timely, although the findings might not be as relevant for assessments now. Studies might not have been backward-looking initially, although many were. Others have been overtaken by time.

More detailed description of the method

Our goal is to compare studies quantitatively and objectively. Our results should be relevant for people who want to know what recent estimates indicate about market impacts of corn starch ethanol, some of whom might want to go on to trace out implications for GHG emissions. Our review decomposes the market effects that lie behind lifecycle GHG estimates into the components. We do so with a view to identify key points of comparison among studies.

The change in GHG emissions from a change in the RFS can be expressed as $\Delta G/\Delta R$, where G is the GHG emission and R is the RFS. We consider the following disaggregation of these steps and paths:

$$\frac{\Delta G}{\Delta R} = \frac{\Delta Q_E}{\Delta R}\left\{g_E + \frac{\Delta P_C}{\Delta Q_E}\left[\sum_i \frac{\Delta Y_i}{\Delta P_C} g_{Yi} + \sum_j \frac{\Delta A_j}{\Delta P_C} g_{Aj}\right] + \sum_k \frac{\Delta Q_k}{\Delta Q_E} g_{Lk} + \sum_f \frac{\Delta Q_f}{\Delta Q_E} g_{Ff}\right\}.$$

The variables are defined as

G	GHG emissions;
R	RFS;
P_C	Corn price;
P_E	Ethanol price;
Q_E	Corn starch ethanol production;
Y_i	Crop yield (i = corn, rice, …);
A_j	Area (j=corn, rice, forest, …);
Q_k	Livestock production (j= beef, chicken, dairy, …);
Q_f	Other liquid fuel production (*f* = gasoline, diesel, other biofuels);
g_E	GHG emissions (fuel emissions only) per unit of corn starch ethanol burned;

g_{Yi} GHG emissions per unit of crop i yield change;
g_{Aj} GHG emissions per unit of area to activity j;
g_{Lk} GHG emissions per unit of livestock product k; and
g_{Ff} GHG emissions (lifecycle) per unit of other liquid fuel product f.

The GHG emissions at various stages (coefficients with "g") are treated as technical parameters. We do not focus on the GHG emissions from the activities themselves, but on economic responses.

There are several complications to applying this equation.

- We must make judgments in some cases in order to determine relevant values from a study.

- The difference operator, Δ, indicates the focus is on ratios of changes. Studies report a mix of absolute and percent changes. We convert percent changes to absolute changes in order to render them all comparable.[2]

- Many of the variables, such as area and livestock, represent a broad range of components that have different GHG emission profiles. Studies do not often report the livestock product effects with great detail.[3]

- Although we do not focus on the technical factors governing GHG emissions, we try to set a framework that does not double-count any emissions. In particular, the change in GHG emissions from burning ethanol, g_E, relates only to tailpipe emissions in this equation whereas other liquid fuel emissions are lifecycle emissions.

Advantages of this method

This method allows us to include more studies in our assessment and to compare them. Many studies are narrowly defined and might generate important information as a consequence of this narrow focus, but would be excluded if we only compared results of studies that report the impact of the RFS on a single, broad indicator.

Another advantage of this approach is that it gives check points that permit us to compare among studies and identify differences. For example, stating that two studies produce different estimates of the impact of corn starch ethanol on land use is not as informative as identifying differences at specific points in the chain of market impacts, such as the change in price given the change in ethanol and the change in land use given the change in price. This representation allows us to see differences along the chain of effects. Alternatively, if two studies present similar overall findings yet have very different impacts at individual stages, then it would be incorrect to conclude that they agree.

We collect additional information about the reviewed studies that could help us to explain differences.

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[2] The conversion of percent changes to absolute changes can be a serious problem. Many studies report percent changes without ever stating base levels. We use actual historical data or projections drawn from various sources, including FAO, EIA, and FAPRI-MU, to convert percent changes to absolute changes in these cases. In some instances, authors were contacted and provided assistance.
[3] For example, GTAP-based studies might report effects on ruminant and non-ruminant aggregates. We apply the percent change in ruminant quantities or prices to beef and milk and the percent change in non-ruminant quantities or prices to pork and poultry.

- How relevant are the numbers? Do effects correspond exactly to what we need? Or do they really include other factors that could be driving agricultural and liquid fuel market impacts?
- What approach is used? Partial-equilibrium (PE) or general equilibrium (GE)? Time series?
- When was the work published? What period of time is assessed?
- If a structural economic approach, then how inclusive is it? How is the RFS represented? How are ethanol and co-product markets represented? Are livestock markets explicit?

We do not conduct a formal meta-analysis at this time.

Disadvantages of this method

We limit ourselves to work since 2010. We also focus narrowly on market impacts. In contrast to our focus on market impacts, other reviews highlight the various additional topics (Adusumilli and Leinder, 2014; Bentivoglio and Rasetti, 2015; Creutzig et al., 2014; Miyake et al., 2012) or of modeling in general (Broch et al., 2013; Panichelli and Gnansounou, 2015; Tokgoz and Laborde, 2014).

We typically omit from these calculations information relating to scenarios that authors provide in order to show partial results or to decompose effects. However, we try to include more information if the scenarios show possible ranges of results.

As emphasized by authors of other reviews, there are a great many reasons why comparisons among studies should be viewed with skepticism. Other reviews reinforce the lesson that estimated results vary widely, but direct comparisons can be undermined by differing scenario definition or other factors (Condon et al., 2015; Khanna and Chen, 2013; Rosegrant and Msangi, 2014; Oladosu and Msangi, 2013;Warner et al., 2014; Zhang et al., 2013).

This brings up the fact that our work required many judgments about how to render sometimes vague or not entirely applicable information to our framework. There is substantial room for error.

Results: Market effects of corn starch ethanol

We summarize ratios measuring market impacts derived from the literature using some or several indicators. The indicators reflect key facts about the distribution of observations, sometimes taking into account the fact that some studies contain multiple scenarios that generate many observations. We use these indicators:

- number of observations or the number of ratios taken from the literature;
- simple average of all observations, so if a study has many scenarios and generates many ratios for each indicator then each ratio is a separate observation;
- weighted average that gives each study a weight of one, so a study that generates many ratios for an indicator counts the same as a study that generates only one ratio;
- 20^{th} and 80^{th} percentiles to give an indication of the dispersion of observations; and

- median or 50th percentile, which is the middle observation.

No indicator is perfect. For example, the simple average shows the central point of the various ratios, but the average might be overly influenced by a few studies that give many observations. An average also might be affected by outliers that, because of some peculiarity in the study or, perhaps, mistake on our own part tends to pull the average up or down. The weighted mean can take into account the fact that all the observations from a single study are not independent of one another, but is still susceptible to outliers. These outlying numbers could come about for any of three reasons:

i. a mistake on our part, meaning that our calculation or our use of the number in this context makes the outlier incorrect,

ii. some element of the original study or studies that generate outliers makes the outliers incorrect, or

iii. mistakes on the part of other authors who generate results that are more narrowly distributed, so only the outliers are correct.

For two of these three possible reasons, it is correct to exclude the outliers, so we also consider the median (50th percentile) as a key indicator. The median is not affected so much by outliers, but only shows the middle value without any regard to the exact pattern of the other observations. We tend to prioritize the median, primarily, and the weighted mean as preferred measures of specific relationships.

Corn price effect

The ratio of corn price change to ethanol quantity change ($\Delta P_C/\Delta Q_E$) is a critical indicator of how large an impact corn starch ethanol has on the market. The value of this ratio is that it gives a general measure of the total corn market response to the demand shock associated with greater demand for corn to use for ethanol and co-products. Studies do not always report the relevant information, but the price impact is often provided in the reviewed studies.

Condon et al. (2015) review studies that estimate the impact of corn starch ethanol on corn price – one of the key ratios of this review. They find, like us, a wide range of reported price impacts in the literature (Table 3). The impacts range from -8% to +85% per billion gallon change in ethanol. Condon et al. (2015) calculate an average impact of +2.9% corn price per billion gallons of corn starch ethanol and +0.24% corn price per 1% more corn starch ethanol. After controlling for various factors, they find "an average price change per billion gallon ethanol increase of three to eight percent" (p 69).

Condon et al. (2015) also track distinguishing characteristics of the source studies. They also seek to determine what drives differences in outcomes. Regarding the change in corn price caused by greater corn starch ethanol, their findings include the following (p. 69-71):

- statistical evidence of a larger corn price impact if co-products are excluded, the oil price is high, or other biofuels change as well; and

- statistical evidence of a smaller corn price impact if the base level of ethanol is larger, a general equilibrium model is used, or for studies that relate to hypothetical conditions in the more distant future.

They find no statistically significant effect or mixed effects for many other possible factors.

Table 3. Estimated corn price impact of corn starch ethanol from Condon et al. (2015) p. 67.

Study	Percent corn price reported in the original study	Percent corn price change per billion gallon ethanol increase
Oladosu et al. (2012)	0.01-0.09	0.008-0.10
Devadoss and Bayham (2010)	3	0.7
Gehlhar et al. (2010)	3-5	0.4-0.7
Mosnier et al. (2013)	-1 to 13	-0.3 to 2
Kruse et al. (2007), Meyer and Thompson (2012), Meyer et al. (2013)	-0.2 to 13	-2.5 to 3.6
U.S. EPA (2010)	3-8	1.3-3.1
OECD-FAO (2008)	6-7	2.0-2.9
Anderson and Coble (2010)	7	7.0
Hochman et al. (2010)	7-12	1.9
Huang et al. (2012)	0.7-45	1.2-2.9
Hertel et al. (2010), Taheripour et al. (2011)	12-24	1.2-2.4
Chakrovorty and Hubert (2013)	18	2.5
Elobeid et al. (2007), Hayes et al. (2009), Babcock (2012)	7-58	1.8-11
Fernandez-Cornejo et al. (2008)	23	2.3
Roberts and Schlenker (2013)	20-30	1.8-2.7
Gohin and Tréguer (2010)	17-50	4.4-11
Cui et al. (2011)	17-44	2.1-3.8
Tyner and Taheripour (2008), Tyner et al. (2010)	5-84	3.6-5.8
Bento and Klotz (2014)	7-85	6.4-10
Huang et al. (2012), Chen and Khanna (2013), Nunez et al. (2013)	-8 to 52	-2.1 to 5.7
Rosegrant et al. (2008)	26-72	2.2-2.6
Model-weighted study	17.8	2.9

Note: we do not reproduce this table in full. Key information that is omitted includes the model and the exact scenario that drives the results. As noted in the text, the inclusion of tax credits, cellulosic biofuel policies, or policies of other countries can complicate the results, possibly explaining many of the negative price impacts.

In making these comparisons, Condon et al. (2015) face many of the same problems we do because study results differ widely in terms of scenario definition, commodity and regional aggregation, and details reported, even before considering fundamental differences in method that might drive results. A key challenge, for example, is addressing whether the changes in biofuel use are motivated by changes in the RFS, tax credits, or some other factor and whether they occur in isolation or alongside other changes in biofuel policies in the U.S. or elsewhere.

We focus on more recent studies (Table 4). We summarize the results for studies published since 2010, excluding literature reviews. We divide the studies into groups based on the extent of the studies' focus on corn starch ethanol.

The first set of studies are understood to change only corn starch ethanol quantity or mandate. There are 34 observations with a simple average of +0.27, meaning that one billion gallons of corn starch ethanol causes the price of corn to rise by +0.27 USD per bushel. The range is fairly broad, with a 20th percentile effect of +0.09 and an 80th percentile effect of +0.33.

Table 4. Change in corn price (USD per bushel) divided by change in corn starch ethanol (billion gallons).

Units: USD per bushel price per billion gallon ethanol	Observ-ations	Averages Weighted	Averages Simple	Percentiles 20th	Percentiles Median	Percentiles 80th
Of the studies focused on corn starch ethanol quantity						
All these studies	36	0.27	0.27	0.09	0.19	0.33
With supply response	26	0.18	0.21	0.09	0.15	0.28
Refereed journal article	12	0.12	0.11	0.04	0.09	0.18
Corn and soybeans, not aggregates	30	0.29	0.31	0.10	0.22	0.33
Distillers grains included	18	0.30	0.26	0.10	0.19	0.33
DG, ethanol trade	11	0.38	0.34	0.19	0.24	0.33
Not assumed to be binding	12	0.36	0.33	0.13	0.22	0.35
General equilibrium model	11	0.18	0.17	0.03	0.09	0.33
Partial equilibrium model	22	0.29	0.27	0.15	0.20	0.33
Greater than 5 b.g. change	10	0.08	0.07	0.03	0.07	0.09
Level of ethanol over 15 b.g.	8	0.15	0.14	0.07	0.12	0.22
Of all studies that provided sufficient information to calculate this ratio						
All studies	66	0.19	0.19	0.03	0.13	0.29
With supply response	56	0.14	0.15	0.03	0.11	0.19
Refereed journal article	23	0.08	0.07	0.03	0.04	0.11
Not refereed	41	0.25	0.26	0.09	0.17	0.33
Not assumed to be binding	16	0.31	0.31	0.13	0.19	0.35
General equilibrium model	24	0.10	0.11	0.02	0.04	0.24
Partial equilibrium model	38	0.22	0.22	0.09	0.16	0.33
Greater than 5 b.g. change	32	0.07	0.07	0.03	0.04	0.12
Level of ethanol over 15 b.g.	18	0.09	0.10	0.03	0.07	0.15

A simple average gives each observation equal weight. However, many studies provide more than one estimate. We do not see these as independent observations. These ratios implicitly reflect the underlying model, so the relationship between the change in corn starch ethanol and corn price might remain fairly similar.

We also provide a weighted average. The weights assign each study an equal value, no matter how many scenarios or experiments are in each individual study. The weighted average price increase for the studies that focus on corn starch ethanol is +0.27.

The drought led to many studies in 2012 that question how biofuel mandate changes would interact with various assumptions about corn yield. These experiments tend to hold area constant and do not allow price response; supply is exogenous. These studies are necessarily only relevant for short run analysis, assessing how an unexpected shock in ethanol affects corn price without allowing time for supply response.

The weighted average of studies focusing on corn starch ethanol that include at least some supply response is +0.18.

The range of observed values is wide. While positive, as expected, the values are below a dime at the 20th percentile to about three times higher at the 80th percentile. Moreover, there are some very high numbers in the literature that drive the weighted and simple averages towards the high end of the range.

The median result in this case is +0.15. The median of the effect for corn starch focused studies with supply response might be the preferred indicator for certain purposes. For example, if a change in policy or fuel markets, domestic or foreign, causes an additional one billion gallons of corn starch ethanol to be made, then this ratio indicates the eventual price impact.

The second set of results for the corn price effect includes all studies with sufficient information to calculate this ratio. These ratios are often inaccurate for our purposes. While we provide them to be inclusive, we do not advocate their use.

The second set of numbers includes a wider set of studies and so might seem more useful. However, the corn price effect might be influenced by other factors apart from the quantity of corn starch ethanol alone. Many studies have many changes blended together, leaving us unable to sort out the effect of corn starch ethanol. Such studies might also shock other components of the US RFS, such as biodiesel, advanced biofuel, or cellulosic biofuel. Other studies shock the policies of more than one country, perhaps including EU mandates, too.

The average corn price effect implied using all studies is +0.19, whether using simple or weighted average. If focusing on the weighted average of studies that allow for supply response, then the average effect drops to +0.14. The median value for all studies and include supply response is +0.11.

We find that certain characteristics of studies are associated with some changes in this ratio. We do not scientifically decompose these possible explanations for varying impacts; a great deal of these relationships might be due to composition changes or tendencies for studies to have multiple traits. For example, all short-run studies without supply response are PE models, many including distillers grain. As many PE models with distillers grains focus on short-run price effects during the drought, the effects are larger. These are also the studies that tend to represent corn and soybeans separately, not as part of broader aggregates.

The median ratio of corn price impact to billion gallon increase in corn starch ethanol quantity tends to be higher in those studies that represent commodities at a more detailed level (corn, soybeans) instead of aggregates (coarse grains, oilseeds). Price effects are larger for those studies that include complications like distillers grains and ethanol trade. Higher price effects with ethanol trade is unexpected: we might normally expect that the possibility for trade would tend to reduce the price impact. However, it might be that studies that allow for trade tend to have other characteristics that more than offset that effect. Refereed journal articles are associated with smaller effects, although a part of this effect is due to the omission of short-run studies without supply response, none of which were published as refereed articles.[4] For distillers grains, Condon et al. (2015) strongly suggest the opposite directional impact, namely that including this co-product leads to lower estimates of corn price impacts from ethanol. As noted earlier, this unexpected result in the

[4] One short-run price shock study was published later in a journal. However, readers are advised in a note on the first page of the journal article to refer to the original, longer study that was not published in a journal. We use the recommended version here.

averages shown here might follow from the likelihood that model characteristics differ systematically and are correlated with each other, so simple comparison of ratios omits important information.

The subset of studies that have larger changes or larger levels of ethanol are associated with smaller median price impacts. This result regarding magnitudes of ethanol is quite similar to that of Condon et al. (2015). If true, sensitivity of price effects to both the level of corn starch ethanol and the change in corn starch ethanol suggest caution when extrapolating results.

Corn production effect

We provide a supplemental measure of effect of corn starch ethanol on the corn market. We calculate the ratio of corn production change to the change in corn starch ethanol ($\Delta Q_C/\Delta Q_E$), that is expressed in billions of bushels per billions of gallons (Table 5).

The studies that focus on corn starch ethanol and include supply response, perhaps the most relevant, suggest that a billion gallons of corn starch ethanol causes +0.10 billion bushels of corn production on (weighted) average or +0.12 billion bushels if using the median. Depending on the exact calculations, this amount of corn might be associated with 30-40% of the increase in corn starch ethanol.[5]

After the median value of 0.12 billion bushels more production, the remaining 60-70% of the total corn needed to produce the additional corn starch ethanol might be drawn from competing demands.

As before, using all studies risks obscuring the impacts of corn starch ethanol because of other changes, such as in cellulosic or other biofuel mandates or in other countries. The weighted average impact of +0.12 billion bushels per billion gallons of corn starch ethanol for all studies might not be the most useful. Just omitting the studies of short-run price response leads to a larger impact of +0.15 billion bushels. The 80th percentile values over +0.2 billion bushels per billion gallons of ethanol suggest that the high-end extreme values of this ratio might be implausible[6] – but for the fact that more than US corn starch ethanol is changing in these cases.

The number of observations is smaller than in the table of corn price impacts. Few studies report the necessary information for this table. Moreover, the majority of those studies addressed price response during the drought and assumed that there would be no production impact associated with corn starch ethanol. Fewer observations increases the risk that outliers will drive the results.

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[5] If we assume that a bushel of corn can be used to make about 2.7 gallons of ethanol, 0.12 billion bushels would imply 0.3 billion gallons of ethanol, or about 30% of the 1 billion gallon ethanol increase. If we were to assume that all the distillers grains co-produced with the ethanol displaced corn that otherwise would go to other uses, such as feed, then the median increase in corn production would account for about 40% of the 1 billion gallon ethanol increase.

[6] Suppose that a 56 pound bushel of corn generates 2.7 gallons of ethanol and 17 pounds of distillers grains. In this case, if a 1 billion gallon increase in ethanol were associated with +0.4 billion bushels, this could result in +1.08 billion gallons of ethanol (more than the original increase) and +3.1 million tons of distillers grains (a bit under a 10% increase over current production). These results would imply that a 0.4 billion bushel increase in production would not only more than suffice to meet the corn starch ethanol increase, but would also generate co-product distillers grains that increase the overall supply of feed. Continuing with this logic, even a +0.3 billion bushel increase in corn production that is devoted for ethanol could theoretically generate more than a billion gallons of ethanol: if all co-produced distillers grains went into feed use and freed up more corn for making ethanol (and yet more distillers grains), then the final increase in ethanol would be more than a billion gallons of ethanol.

Table 5. Change in US corn production (billion bushels) divided by change in corn starch ethanol (billion gallons).

Units: billions of bushels per billion gallons	Obs.	Average Weighted	Average Simple	Percentiles 20th	Percentiles Median	Percentiles 80th
Of the studies focused on corn starch ethanol quantity						
All these studies	18	0.05	0.05	0.00	0.00	0.12
With supply response	8	0.10	0.11	0.09	0.12	0.13
Refereed journal article	5	0.11	0.12	0.10	0.11	0.14
Corn and soybeans, not aggregate	7	0.11	0.11	0.11	0.12	0.13
Not assumed to be binding	3	0.00	0.00	n.a.	0.00	n.a.
Greater than 5 b.g. change	4	0.07	0.08	0.10	0.10	0.12
Of all studies that provided sufficient information to calculate this ratio						
All studies	35	0.12	0.15	0.00	0.11	0.23
With supply response	25	0.15	0.21	0.11	0.17	0.25
Refereed journal article	11	0.13	0.16	0.11	0.13	0.25
Not assumed to be binding	9	0.07	0.05	0.00	0.00	0.05
Greater than 5 b.g. change	20	0.16	0.22	0.11	0.20	0.27

Land use impacts

Land use impacts or indirect land use change ($\Delta A_j / \Delta P_C$) are key factors in lifecycle GHG emission calculations. Deforestation induced by price changes can play an important part in some GHG emission calculations. On the other hand, new land uses can also decrease GHG emissions, such as if methane-emitting rice area is reallocated to uses with lower GHG emissions.

The ranges of estimates that we find reinforce the uncertainty of indirect land use change caused by changing biofuel quantities, and the associated GHG emissions. We must be somewhat agnostic about whether this is area planted or area harvested, as many studies are not explicit. Definitions of larger aggregates, cropland and forest area, vary among studies.

Corn or coarse grains, Soybeans or oilseeds

For the studies focusing on corn starch ethanol and allowing for supply response, the median effect of an additional dollar in the corn price is +10-11 million acres more corn or coarse grains in general in the U.S. (Table 6). If we assess these values based on recent market data, then the area increase is about 10-12% and the change of one dollar represents an increase in the corn price of about 25%. Comparing these numbers implies a US corn area elasticity of 0.4-0.5. This calculated value is probably not an average value of actual model elasticities. First, the models often have cross-commodity effects and take into account soybean market changes, so the ratios presented here implicitly account for those relationships as well as the own-price effect. Second, the median hides a very wide range.

Table 6. Change in land use (million acres) divided by change in corn price (USD per bushel).

Units: millions of acres per USD per bushel price	Corn or coarse grain area: United States Obs	Avg	Median	Corn or coarse grain area: World Obs	Avg	Median	Soybean or oilseed area: United States Obs	Avg	Median	Soybean or oilseed area: World Obs	Avg	Median
Of the studies focused on corn starch ethanol quantity												
All these studies	21	8.6	0.0	4	38.1	47.3	10	-1.6	0.0	4	-4.3	-2.6
With supply response	11	14.5	10.4	4	38.1	47.3	4	-3.1	-0.9	4	-4.3	-2.6
Refereed journal article	5	25.7	42.8	4	38.1	47.3	2	-5.4	-5.4	4	-4.3	-2.6
Corn and soybeans, not aggregate	15	4.0	0.0	1	23.7	23.7	10	-1.6	0.0	1	-7.1	-7.1
Not assumed to be binding	10	4.0	0.0	1	23.7	23.7	8	-2.2	0.0	1	-7.1	-7.1
Greater than 5 b.g. change	6	26.5	26.7	3	52.5	48.4	3	1.0	1.4	3	-1.6	1.8
Of all studies that provided sufficient information to calculate this ratio												
All studies	35	12.0	7.6	7	28.7	46.1	21	-1.3	0.0	7	54.3	4.6
With supply response	25	15.2	12.1	7	28.7	46.1	15	-1.7	-3.1	7	54.3	4.6
Refereed journal article	14	19.6	18.4	7	28.7	46.1	8	-1.0	-5.4	7	54.3	4.6
Not assumed to be binding	11	5.7	0.0	1	23.7	23.7	9	-1.9	0.0	1	-7.1	-7.1
Greater than 5 b.g. change	14	18.3	16.4	6	30.0	47.3	9	2.6	1.4	6	69.7	37.2

Notes: (1) the average shown in this table gives each study a weight equal to one, so studies with multiple observations are not given more weight than other studies with fewer observations; and (2) corn and soybean area responses shown are often actually impacts on aggregated coarse grain area and oilseed area, particularly in general equilibrium studies.

Studies report strong area effects in a few instances. Very high values are a cause of concern. Corn area does not appear to have moved up or down by nearly such an amount even though prices have risen and fallen by much more than a dollar over the past decade. A casual comparison to historical data does not disallow a very strong response, but the apparent discrepancy is a cause of concern.

If the reports that focus on short-run response during the drought are included, then the corn area effect is necessarily smaller. The mean drops by half and the median is zero for studies focusing on corn starch ethanol. The frequent use of partial equilibrium models with corn and soybean identified for short-run analysis might offer some explanations why the effects in these cases are lower.

The average land use impacts of all studies also suggests greater corn area, even if corn starch ethanol alone is not the sole driving force. The range of values is far wider: there can be negative values in the event that other biofuel feedstock demands cause greater market price impacts than corn starch ethanol causes on the corn market.

Increases in corn area might be partly at the expense of soybeans, although there are also other sources (of which, cropland changes are shown later). There is indirect land use change in the U.S. according to most estimates. The average reduction in soybean area among studies that focus on corn starch ethanol and that allow supply response is -3 million acres per dollar increase in the corn price and the median effect is -1 million acres. This result is defined by only a few observations.

World corn and soybean area impacts are based on very few observations, but tend to go in the same direction as US effects for studies that focus on corn starch ethanol. World effects are larger than US-only effects, suggesting rest of world area response tends to build on the US changes.

The relative sizes suggest that the reduction in soybean area accounts for a small portion of the change in corn area in the U.S. More studies report corn area effects than soybean impact and there might be some systematic differences that explain the different impacts. Separately, we compare corn and soybean impacts study-by-study. For the few studies that focus on corn starch ethanol, include supply response, and report both numbers, the lower soybean area accounts for about one-fifth of the increase in the US corn area.

Broader scenarios that focus more broadly than on corn starch ethanol alone often result in higher global soybean area. Many of these studies increase the US biodiesel mandate or the EU mandate. Changes to the EU mandate are particularly likely to affect global oilseed production given the heavy focus on biodiesel.

We find even fewer clearly defined ratios relating to other land uses. For example, there are few studies that report reduced rice area if corn starch ethanol or corn price increase. If rice area changes can have larger GHG emission effects than production of some other crops, then this effect might be important, but there is insufficient information available in the reviewed studies to draw any conclusions.

Broader land use impacts

Here, again, the number of observations is quite low and the results might be sensitive to the methods and assumptions of individual studies. Moreover, the exact results might not always be comparable because studies define cropland or forest area differently. For example, GE models appear to rely on a broad definition of arable and permanent cropland associated with FAOSTAT data whereas PE models might define cropland as the total of a smaller set of uses (Table 7).

Table 7. Change in broader land use (million acres) divided by change in corn price (USD per bushel).

	Cropland area						Forest area					
Units: millions of acres	United States			World			United States			World		
per USD per bushel price	Obs	Avg	Median	Obs	Avg	Median	Obs	Avg	Median	Obs	Avg	Median
Of the studies focused on corn starch ethanol quantity												
All these studies	7	1.5	0.0	5	25.4	33.8	6	0.0	0.0	3	-10.2	-11.7
With supply response	1	6.1	6.1	5	25.4	33.8	0	n.a.	n.a.	3	-10.2	-11.7
Refereed journal article	1	6.1	6.1	5	25.4	33.8	0	n.a.	n.a.	3	-10.2	-11.7
Corn and soybeans, not aggregate	7	1.5	0.0	2	18.0	18.0	0	n.a.	n.a.	3	-10.2	-11.7
Not assumed to be binding	7	1.5	0.0	1	2.1	2.1	6	0.0	0.0	0	n.a.	n.a.
Greater than 5 b.g. change	1	0.0	0.0	4	37	39	1	0.0	0.0	3	-10.2	-11.7
Of all studies that provided sufficient information to calculate this ratio												
All studies	23	8.6	3.6	13	26.3	13.7	14	-7.0	0.0	10	-83.4	-8.1
With supply response	17	10.9	6.1	13	26.3	13.7	7	-9.3	0.0	10	-83.4	-8.1
Refereed journal article	14	10.3	5.1	12	28.1	15.5	7	-4.7	0.0	10	-83.4	-8.1
Not assumed to be binding	8	2.0	0.0	2	7.9	7.9	6	0.0	0.0	0	n.a.	n.a.
Greater than 5 b.g. change	13	5.1	3.6	12	29.7	18.5	9	-10.2	0.0	10	-83.4	-8.1

Notes: (1) the average shown in this table gives each study a weight equal to one, so studies with multiple observations are not given more weight than other studies with fewer observations; and (2) definitions of cropland and forest area vary among studies.

Allowing supply response and focusing on corn starch ethanol, the impact of a dollar higher corn price (plus other factors that might drive the change) is about 6 million acres more cropland in the U.S. in the single observation that fits these criteria. Any implication that a dollar change in corn price would lead to a large increase in total US cropland might be compared to recent price changes as compared to less variable total cropland area. This comparison sidesteps the problem of few observations available for the effects calculated here and the variety of factors that could drive historical land use. The appropriate representation for studies that assume no US crop supply response should, in principle, be zero changes in US cropland area and forest area, as well.

World cropland area also increases according to these few studies, with the weighted average suggesting +25 million acres for a one dollar change in corn price and the median change at +34 million acres. World forest area decreases according to weighted average and median results. However, the small number of observations and likely mismatched definitions of U.S. and world land aggregates among these studies discourage strong conclusions.

The results of all studies, including those that do not focus only on corn starch ethanol, can be different from the results of studies focusing only on corn starch ethanol. And, again, some of this difference is driven by biodiesel, cellulosic, or advanced mandates, other policies in the U.S., or policies in other countries, but there are other problems, as well. Some part of the difference is probably caused by the changing composition of studies included given that only a few studies provide sufficient information for each calculation. For example, it is perhaps unwise to draw strong conclusions by comparing the impacts of all 17 observations that allow for supply response on US cropland and the forest area effect of 7 relevant observations. Another important challenge in dealing with broad cropland and forest area aggregates is that the definitions vary among models. The potential for incorrect comparisons is larger when studies report relative changes that we convert into absolute changes without knowing the base values.

Land use impact based on corn ethanol quantity

Studies do not often report numbers in a way that allows us to define many of the land impacts. In many cases, GHG emissions associated with land use change might be reported, but without sufficient details in the published work to extract the information that we need. This omitted step renders the preceding tables at least somewhat unreliable. A single study that generates strong numbers can drive many results.

Table 8. Change in US corn area (million acres) divided by change in corn starch ethanol (billion gallons).

Units: millions of acres per billion gallons of ethanol	Observ-ations	Averages		Percentiles		
		Weighted	Simple	20th	Median	80th
Of the studies focused on corn starch ethanol quantity						
All these studies	24	0.7	0.6	0.0	0.5	1.2
With supply response	14	1.0	1.0	0.6	1.0	1.4
Refereed journal article	7	0.9	0.9	0.8	1.1	1.2
Corn and soybeans, not aggregates	16	0.7	0.5	0.0	0.0	1.2
Distillers grains included	14	0.6	0.5	0.0	0.3	1.2
DG, ethanol trade	8	0.6	0.4	0.0	0.0	1.1
Not assumed to be binding	10	0.5	0.3	0.0	0.0	1.0
General equilibrium model	10	0.9	0.8	0.0	1.0	1.6
Partial equilibrium model	17	0.5	0.3	0.0	0.0	0.8
Greater than 5 b.g. change	8	0.6	0.6	0.2	0.6	1.1
Level of ethanol over 15 b.g.	5	0.7	0.7	0.4	0.5	1.2
Of all studies that provided sufficient information to calculate this ratio						
All studies	37	0.7	0.7	0.0	0.7	1.3
With supply response	27	0.9	1.0	0.6	1.1	1.5
Refereed journal article	14	0.9	1.0	0.6	1.0	1.4
Not refereed	23	0.7	0.6	0.0	0.4	1.3
Not assumed to be binding	11	0.6	0.4	0.0	0.0	1.1
General equilibrium model	13	0.7	0.7	0.0	0.7	1.5
Partial equilibrium model	27	0.7	0.6	0.0	0.6	1.3
Greater than 5 b.g. change	16	0.7	0.7	0.1	0.7	1.3
Level of ethanol over 15 b.g.	11	0.6	0.7	0.1	0.6	1.1

Note: corn area responses shown are often actually impacts on aggregated coarse grain area, particularly in general equilibrium studies.

We supplement the target ratio with an additional ratio drawn from the literature, namely the change in crop area divided by the change in corn starch ethanol quantity ($\Delta A_j/\Delta Q_E$). The units of this ratio are million acres of area per billion gallons of corn starch ethanol. The ratio is provided for US and world corn or coarse grain area (Table 8).

The weighted average and median corn area impact of a billion gallons of ethanol for those cases that allow supply response is a million acres more corn or coarse grain in the US. This amount seems potentially consistent with the requirement.[7] The implication is that between a third and a half the total volume of additional corn required for the increase in corn starch ethanol is met with new production, with the other part presumably associated with reductions in other uses of corn.

Other results shown here include complications. Many of the studies that report the necessary information assume no area response. These studies focus on the short-run market conditions during the recent drought. Other studies might reflect other changes. For example, if all studies are used then the corn area expands, but it is not clear how cross effects from US or EU biodiesel mandates, US cellulosic biofuel requirement, tax credits, or other factors influence these numbers.

A similar comparison of US cropland use to corn starch ethanol provides another way to estimate land use change (Table 9). The change in composition of studies included in the summary statistics makes it difficult to compare US corn area and cropland area effects. Looking at the studies focused on corn starch ethanol and allowing supply response, however, the weighted average effect is +0.7 million acres of cropland and the median impact is +0.2 million acres. Some studies seem to imply high area impacts from corn starch ethanol. Again, these extreme cases might reflect errors on our part in interpreting the results, or other factors that would lead one to discount the outliers, so the median result might be seen as a more reliable indicator.

Including all studies, even those not focused on corn starch ethanol, suggests roughly similar cropland impacts per gallon of corn starch ethanol as for the first set of studies, but the driving factors might be different.

[7] If yield were 165 bushels per acre and each bushel could be used to make 2.7 gallons of ethanol, then 2.25 million more acres planted to corn would already generate enough ethanol to account for the additional biofuel. If feed displaced by distillers grains co-produced with corn starch ethanol were also included, then even less corn area is required.

Table 9. Change in US cropland use (million acres) divided by change in corn starch ethanol (billion gallons).

Units: millions of acres per billion gallons of ethanol	Observ-ations	Averages Weighted	Simple	Percentiles 20th	Median	80th
Of the studies focused on corn starch ethanol quantity						
All these studies	18	0.5	0.5	0.0	0.1	0.2
With supply response	12	0.7	0.8	0.0	0.2	0.5
Refereed journal article	9	0.9	1.0	0.0	0.2	1.8
Corn and soybeans, not aggregates	9	0.9	0.9	0.0	0.0	1.8
Distillers grains included	18	0.5	0.5	0.0	0.1	0.2
DG, ethanol trade	16	0.6	0.6	0.0	0.1	0.2
Not assumed to be binding	7	0.1	0.1	0.0	0.0	0.0
General equilibrium model	12	0.1	0.1	0.0	0.1	0.2
Partial equilibrium model	9	0.9	0.9	0.0	0.0	1.8
Greater than 5 b.g. change	9	0.1	0.1	0.0	0.1	0.2
Level of ethanol over 15 b.g.	3	2.0	2.6	1.6	3.7	3.9
Of all studies that provided sufficient information to calculate this ratio						
All studies	33	0.6	0.5	0.0	0.1	0.7
With supply response	27	0.7	0.7	0.0	0.2	1.0
Refereed journal article	18	0.2	0.2	0.0	0.1	0.3
Not refereed	13	0.6	0.5	0.0	0.1	1.1
Not assumed to be binding	8	0.5	0.3	0.0	0.0	0.3
General equilibrium model	19	0.1	0.1	0.0	0.0	0.2
Partial equilibrium model	17	1.0	1.0	0.0	0.5	1.8
Greater than 5 b.g. change	21	0.4	0.3	0.0	0.1	0.3
Level of ethanol over 15 b.g.	10	0.9	1.1	0.1	0.3	1.5

Yield impacts

Yield impacts ($\Delta Y_i/\Delta P_C$ or $\Delta Y_i/\Delta Q_E$) are a key source of crop supply that might be associated with fewer GHG emissions than an expansion in total cropland that cuts into forest area. The potential for yield response to help to meet some or much of the production impact has been recognized both early in the analysis of biofuel impacts (Keeney and Hertel, 2009) and in the context of observed changes in production, land use, and productivity in recent years (Babcock and Iqbal, 2014).

The number of estimated yield impact ratios that we can calculate based on studies published since 2010 is quite limited. Few studies report this information. Apart from the studies focused on short-run impacts, many or perhaps most other studies include some possibility of yield response to rising crop prices.

Livestock market impacts

The potential impacts on livestock markets can be consequential for GHG emissions, but are often not included, not reported, or not reported in a way that allows us to standardize the comparison. We supplement the target ratio with two additional ratios drawn from the literature.

The first ratio is the change in livestock production divided by the change in corn starch ethanol quantity ($\Delta Q_k/\Delta Q_E$). The units of this ratio are million tons produced per billion gallons of corn starch ethanol (Table 10). The second, supplemental ratio is the change in livestock prices divided by the change in corn starch ethanol quantity ($\Delta PL_k/\Delta Q_E$). The units of this ratio are dollars per ton per billion gallons of corn starch ethanol (Table 11).

There are few observations in many of these instances, so only a few indicators are useful. The distinction between studies that focus on corn starch ethanol and broader studies could remain important. For example, a study that changes biodiesel requirements in the U.S. or EU by a substantial amount relative to the corn starch ethanol change could lead to rising demand for vegetable oil, more oilseed crush, and lower meal and feed prices, at least for some types of livestock, even though the corn price is higher. In the comparisons below, compositional effects are probably too strong to speak confidently to this possibility.

Table 10. Change in US livestock quantities (million tons) divided by change in corn starch ethanol (billion gallons).

Units: millions of tons	Beef			Milk			Pork			Poultry		
per billion gallons of ethanol	Obs	Avg	Median	Obs	Avg	Median	Obs	Avg	Median	Obs	Avg	Median
Of the studies focused on corn starch ethanol quantity												
All these studies	4	-0.01	-0.02	2	-0.33	-0.33	4	-0.06	-0.07	4	-0.04	-0.05
Refereed journal article	4	-0.01	-0.02	2	-0.33	-0.33	4	-0.06	-0.07	4	-0.04	-0.05
Corn and soybeans, not aggregates	3	-0.01	-0.02	2	-0.33	-0.33	3	-0.07	-0.12	1	-0.02	-0.02
Of all studies that provided sufficient information to calculate this ratio												
All studies	8	-0.01	-0.01	6	-0.11	-0.05	8	-0.03	-0.02	8	-0.03	-0.03
Refereed journal article	4	-0.01	0.00	2	-0.03	-0.03	4	-0.01	-0.02	4	-0.01	-0.01
Greater than 5 b.g. change	5	-0.01	-0.01	4	-0.04	-0.04	5	-0.01	-0.02	5	-0.02	-0.02

Note: the average shown in this table gives each study a weight equal to one, so studies with multiple observations are not given more weight than other studies with fewer observations.

The average price and quantity impacts are in the expected directions. Higher biofuel and demand for biofuel feedstocks is associated with lower quantities and higher prices of livestock products. The negative impact on livestock production is consistent with the result given earlier that a part of the increase in corn used for ethanol and co-product production comes from other uses, at least if evaluated using the median corn production change for the case of corn starch ethanol focus with corn supply response. This broad assessment risks overlooking the scope for rising ethanol production, which causes greater competition for corn but more supplies of distillers grains, to have different feed costs impacts for different animal types, as well as the complications of cross-price effects in meat demands.

Table 11. Change in US livestock prices (USD per ton) divided by change in corn starch ethanol (billion gallons).

Units: USD per ton	Beef			Milk			Pork			Poultry		
per billion gallons of ethanol	Obs	Avg	Median	Obs	Avg	Median	Obs	Avg	Median	Obs	Avg	Median
Of the studies focused on corn starch ethanol quantity												
All these studies	6	11.0	3.8	2	4.3	4.3	6	15.1	4.0	6	13.6	3.9
Refereed journal article	3	16.7	31.6	2	4.3	4.3	3	23.7	41.3	3	22.3	37.7
Corn and soybeans, not aggregates	4	14.1	17.7	2	4.3	4.3	4	19.0	21.7	2	n.a.	n.a.
Of all studies that provided sufficient information to calculate this ratio												
All studies	8	7.9	3.7	4	1.7	2.1	8	10.1	2.9	8	9.4	2.6
Refereed journal article	3	0.7	1.3	2	0.4	0.4	3	1.7	2.1	3	2.1	2.1
Greater than 5 b.g. change	2	2.5	2.5	2	0.4	0.4	2	1.5	1.5	2	2.0	2.0

Note: the average shown in this table gives each study a weight equal to one, so studies with multiple observations are not given more weight than other studies with fewer observations.

For scale, the results of this table can be compared to recent quantities and prices.[8] The US quantity results constitute changes of -0.1% beef, -0.4% milk, -0.5% pork, and -0.2% poultry if assessed using the weighted average of studies focused on corn starch ethanol. The relative impacts implied by all studies are generally smaller, particularly for milk. The median impacts are mostly stronger, at -0.2% for beef, -0.4% for milk, -0.7% for pork, and -0.2% for poultry.

The price impacts of the studies focused on corn starch ethanol are about 1% or less if judged using the weighted average. The median, however, suggests that the effects are less than half as much, except in the case of pork.

The role of distillers grains is not always clearly defined. For some studies, we are unsure if the underlying model represents distillers grains and, if so, how.

Fuel market impacts

Fuel market impacts ($\Delta Q_f / \Delta Q_E$) are another source of GHG emissions. The impact of a billion gallons of corn starch ethanol on emissions might be at its largest if it reduces US gasoline use by an equivalent amount, in energy terms, and there is no offsetting change. However, the lower gasoline use in the U.S. will cause gasoline prices to fall so buyers in other countries will increase their gasoline use. The size of these impacts, as well as cross effects on other fuels, is an empirical question. Moreover, there is the potential for broad impacts on overall fuel use if a biofuel mandate raises consumer fuel costs in some way.

Serra and Zilberman (2013) summarize much of the literature on price links relating to energy markets. Their review includes many older studies about petroleum-biofuel-agriculture price links, however, whereas we focus on recent information. Moreover, they review studies that rely heavily on time series methods, with only limited reference to models that represent market equilibria explicitly. Time series studies using years of historical data fundamentally represent markets for biofuels, petroleum and petroleum products, and

[8] We use average 2010-14 values.

agricultural commodities in those historical periods. These studies might have limited relevance to forward-looking assessment or might omit information that we have available since 2010. For example, data used in time series studies probably do not reflect the blend wall that might now be a critically important determinant of price links.

Serra and Zilberman make no mention of any study using recent RIN price data, even though these prices can usefully signal which biofuel mandates are binding (Whistance and Thompson, 2014; Whistance, Ripplinger, and Thompson, 2016). The sharply higher RIN prices in the last few years and corresponding increase in RFS compliance costs presumably lead to some market and price impacts. Firms or people involved in fuel markets might be affected: refiners might have higher costs and consumers might pay higher prices, for example.

More generally, the common use of high frequency time series data to estimate price links might be compared to the previous results that suggest corn price impacts of corn starch ethanol are larger (a) if assessed before allowing supply response, and (b) for smaller changes in corn starch ethanol. For example, monthly data might tend to reflect short-run market responses to small changes. Time series methods can include lags and delayed effects, so the potential for measuring short-run price links might be avoided.

Our review of the literature provides some information that is directly relevant. The estimated impacts of corn starch ethanol on diesel, biodiesel, and other types of ethanol are too few and often complicated because the final results are driven by other changes, such as in biodiesel mandates. The results for gasoline effects offer some insights about recently published studies (Table 12).

The effect of a billion gallons of ethanol on gasoline use in the U.S. is negative. This result tends to follow expectations: more ethanol on the market could lead to less use of competing fuels. This number is not measured in energy equivalence: the trade off in terms of energy implied is more than one-for-one.

More than a one-for-one trade-off between ethanol and gasoline is possible if the increase in ethanol is accompanied by greater compliance costs that are passed on to US consumers, although whether or not that reason is the actual one for each source study is not known. Studies with higher costs of ethanol supply as compared to gasoline supply (Drabik and de Gorter, 2011) and others that explicitly model commodity, biofuel, and petroleum product supplies as well as RFS compliance costs (Pouliot and Babcock, 2014; Thompson et al., 2011) suggest that fuel cost implications can play a role alongside the substitution among fuels.

Rest of world fuel use rises as expected given that the lower US gasoline use would lead to lower prices to buyers in other countries. For the studies focused on corn starch ethanol, comparing the rest of world to the US average effects suggests the net impact on global gasoline quantities of -0.3 to -0.4 billion gallons of gasoline per billion gallons of US corn starch ethanol. Some of the difference might be explained by differences in the studies as we find fewer that report rest of the world impacts. Nevertheless, the numbers suggest that the net effect on global fuel markets of a billion gallons of additional ethanol is a smaller increase in overall fuel use if judged in gasoline equivalent terms.

Table 12. Change in gasoline use (billion gallons) divided by change in corn starch ethanol (billion gallons).

Units: billion gallons per billion gallons	United States			Rest of the world		
	Obs	Avg	Median	Obs	Avg	Median
Of the studies focused on corn starch ethanol quantity						
All these studies	9	-0.8	-0.8	5	0.4	0.5
Refereed journal article	5	-0.9	-0.9	5	0.4	0.5
Not assumed to be binding	0	n.a.	n.a.	0	n.a.	n.a.
Greater than 5 b.g. change	5	-0.9	-0.9	5	0.4	0.5
Of all studies that provided sufficient information to calculate this ratio						
All studies	23	-2.3	-0.9	8	1.5	0.5
With supply response	23	-2.3	-0.9	8	1.5	0.5
Refereed journal article	8	-4.3	-1.0	7	2.4	0.5
Not assumed to be binding	4	-1.1	-0.6	1	n.a.	n.a.
Greater than 5 b.g. change	13	-1.2	-0.9	7	-0.2	0.5

Note: the average shown in this table gives each study a weight equal to one, so studies with multiple observations are not given more weight than other studies with fewer observations.

Broader studies often include a variety of changes, potential including biodiesel and ethanol made from other feedstocks. These results are less likely to be applicable and might even be misleading. For example, a study that increases corn starch and cellulosic ethanol might have a high ratio of gasoline effect divided by corn starch ethanol change.

More troubling comparisons are from studies that include US tax credits to blending biofuels. In contrast to biofuel mandates that cause costs to the industry that must be paid and will tend to lower overall fuel use, the tax credit represents a transfer from taxpayers that will tend to increase overall fuel use. These two types of policies are expected to have opposite impacts on overall fuel use and, potentially, on GHG emissions (Thompson, Meyer, and Westhoff, 2010; Thompson, Whistance, and Meyer, 2011).

Other lessons from the literature

RFS impacts on markets or GHG emissions

The change in markets or GHG emissions associated with a change in the RFS is not the same as the change associated with change in corn starch ethanol. Extrapolating the results above to infer the impacts of the RFS can be misleading, particularly if the goal is to assess the impacts of the RFS as it relates to corn starch ethanol.

There are several possible errors if indicators of corn starch ethanol effects are used to indicate the effects of changes to the RFS.

a) The definition of the change in the RFS is critical. Should the denominator be the change in the total volumes associated with the RFS? Or just the corn starch ethanol component?

b) An increase or decrease in the mandated volumes does not have to cause an equal change in biofuel quantities used. The mandates need not be binding.

c) The mandate might not remain binding. For a large decrease, an initially binding requirement might at some point cease to be binding.

d) This question of binding and non-binding mandate as it applies to corn starch ethanol is further complicated. The nested RFS allows the component associated with the corn starch ethanol to be met using other biofuels – there is no corn starch ethanol mandate (Thompson et al., 2010; Whistance and Thompson, 2014). Increases in the RFS that might appear to affect conventional ethanol can be met with biodiesel, for example.

e) The mandate relates to renewable fuel use in the US, not production, so trade changes might offset some or most of changes in domestic use, implying smaller changes in US agricultural commodity markets than might otherwise be expected.

Many studies we review assume that an increase in the mandate as it relates to corn starch ethanol causes a one-for-one increase in corn starch ethanol. The potential for other biofuels, such as biodiesel, to meet the increase in the overall mandate is frequently omitted.

Extrapolating from the effects of a billion gallon change in corn starch ethanol to the impacts of the RFS in total seems to ignore many of these factors. A complete elimination of the RFS would not cause an equal change in biofuel volumes used or produced as long as some demand for these fuels remains, including at least as a fuel additive.

Other sensitivities

Comparisons will contain errors

Studies typically report percent changes or absolute changes. We choose to compare effects based on relative absolute changes – the ratios – but this choice could affect results.[9]

Converting relative changes into absolute changes was necessary to make our comparisons, but we often had to make some assumptions. Few studies give base values. Even for historical data, it can be difficult to track down the precise starting point of data for a particular study. In instances where base data are partially updated or even projected, many studies do not provide the initial levels so we are left to apply the percent changes to some other data source, despite the potential for error.

Scenario definitions

Estimated impacts depend on market context. We identify differences based on whether or not studies permit supply response. A study that focuses on short-run impacts given production tend to estimate larger price impacts. However, not all studies that allow some supply response necessarily allow full supply or

[9] Many authors responded to requests for additional information on this or other matters. This gracious assistance does not preclude the possibility for errors in how the numbers are used, but certainly reduces the risk.

demand response. If a simulation model shows results after 2 or 3 years, then there is some area allocation response, but there might not yet be sufficient time for the full market response, including yield response, if the price shock is large and sustained.

The size of the biofuel increase also seems to matter, suggesting decreasing marginal impact as the ethanol production increase rises.

Baselines matter

Baselines might also affect results. For example, the studies that have larger initial volume of biofuel use tend to have much smaller price impacts of an additional billion gallons of ethanol.

There might be other market implications tied to the baseline. For example, initial crop stocks could be a source of sensitivity. If corn stocks are low to begin with, then the price impact of additional demand might lead to a bigger price effect as compared to an alternative initial setting with ample stocks.

GHG calculations have been shown to be sensitive to baselines, with different emission implications from ethanol-induced pressure to increase crop area depending on the context (Koverpris and Mueller, 2012; Thompson et al., 2014). If the setting is one of rising land used for crops, then the pressure is manifested in further land expansion, potentially leading to deforestation and an accompanying surge in GHG emissions. If overall land allocated to crops is falling, then the pressure for more land delays the exit of land from crop production. Not only does this latter case make deforestation surges less likely, the implications for GHG emissions might be sensitive to the alternative use to which the former cropland would otherwise have been allocated.

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