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Sources of corn for ethanol production in the United States: a decomposition analysis of the empirical data

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Abstract: The use of corn for ethanol production in the United States quintupled between 2001 and 2009, generating concerns that this could lead to the conversion of forests and grasslands around the globe, known as indirect land-use change (iLUC). Estimates of iLUC and related 'food versus fuel' concerns rest on the assumption that the corn used for ethanol production in the United States would come primarily from displacing corn exports and land previously used for other crops. A number of modeling efforts based on these assumptions have projected significant iLUC from the increases in the use of corn for ethanol production. The current study tests the veracity of these assumptions through a systematic decomposition analysis of the empirical data from 2001 to 2009. The logarithmic mean divisia index decomposition method (Type I) was used to estimate contributions of different factors to meeting the corn demand for ethanol production. Results show that about 79% of the change in corn used for ethanol production can be attributed to changes in the distribution of *domestic* corn consumption among different uses. Increases in the domestic consumption share of corn supply contributed only about 5%. The remaining contributions were 19% from added corn production, and –2% from stock changes. Yield change accounted for about two-thirds of the contributions from production changes. Thus, the results of this study provide little support for large land-use changes or diversion of corn exports because of ethanol production in the United States during the past decade. © 2011 Society of Chemical Industry and John Wiley & Sons, Ltd

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Keywords: biofuel; indirect land-use change; corn ethanol; index decomposition analysis

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Introduction

Ethanol production in the United States grew at an average annual rate of about 25% between 2001 and 2009 because of a combination of policy and market developments. Beginning in 2000, several states passed legislation to restrict or ban the use of methyl tertiary butyl ether (MTBE) as an additive (oxygenate) in gasoline to address water-contamination issues.[1] In addition, the USA Federal Energy Policy Act of 2005 required the nationwide removal of MTBE from all gasoline and established a renewable fuel standard (RFS) with a target of 7.5 billion gallons by 2012. The Energy Independence and Security Act (EISA) of 2007, also known as RFS2, increased the target to 36 billion gallons by 2022. The amount from conventional biofuels, mainly corn ethanol, is limited to a maximum of 15 billion gallons, and the remaining 21 billion gallons or more are to be derived from advanced biofuels, such as cellulosic ethanol and biomass-based diesel.[2] The EISA also required each biofuel category to meet thresholds for reductions in lifecycle greenhouse gas (GHG) emissions relative to gasoline. Along with these policy developments, the demand for liquid fuels began to increase in 2003 as the global economy surged. Given that global oil production capacity had stagnated during the previous decade, ready substitutes for petroleum products, such as ethanol, became increasingly attractive. In the USA, these developments led to increases in annual corn-ethanol production from 1.8 billion gallons in 2001 to 10.6 billion gallons in 2009. By late 2010, annual production was projected to exceed 12.5 billion gallons, and installed capacity totaled 13.5 billion gallons, with another 1.3 billion gallons under construction that would bring production capacity up to the current regulatory cap.[3]

The environmental and welfare benefits of corn-ethanol production have been questioned by a number of analysts based on its potential indirect effects. First, increases in global crop prices were assumed to result from the diversion of corn exports to ethanol production. This came to be known as the 'food-versus-fuel' debate.[4] Second, it was suggested that corn-ethanol production would lead to indirect land-use change (iLUC), which is defined as the conversion of forests and other natural lands around the globe to agriculture to replace grain or cropland diverted to biofuels.[5]

The effects of the use of corn for ethanol production are determined by interactions among multiple markets. Figure 1 identifies a subset of these markets (land, corn, other crops/livestock, and other commodities) that interact at the local, national, and global scales. ILUC emanates mainly from changes in net exports and the competition

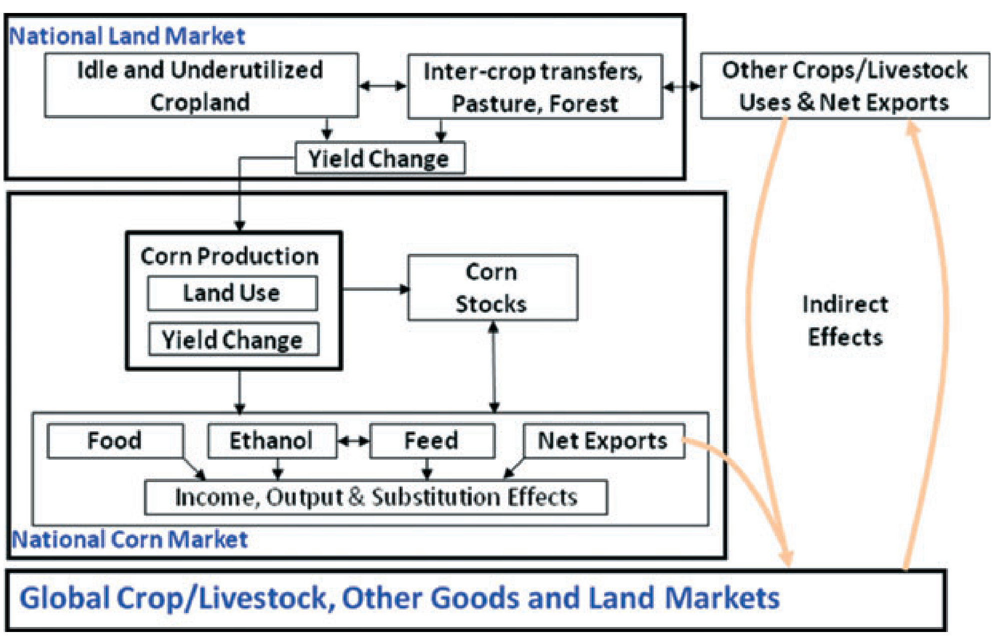

Figure 1. Processes driving the indirect impacts of corn used for ethanol.

between corn and other crops or livestock for land. However, tracing the sources of changes in the processes leading to iLUC identified in Fig. 1 is not straightforward. For example, land-use and crop choices by farmers are influenced by many social, economic, and market factors, subject to a wide range of policy environments worldwide. Similarly, adjustments in the uses of corn and other grains (e.g. for livestock feed) are driven by the availability of substitutes as well as by local and global market conditions.

Simulations of the indirect effects of corn-ethanol production have been conducted with both partial-equilibrium models (focusing on the agricultural and forestry sectors) and general-equilibrium models (incorporating all sectors of the economies of interest). Partial-equilibrium models (e.g. FAPRI/FASOM*) tend to be more detailed but neglect crucial economy-wide interactions that are captured in general-equilibrium models.[6] However, the economy-wide scope of general-equilibrium models (e.g. GTAP†) makes it impractical for those models to represent the same level of detail as do partial-equilibrium models.[7] In addition to differences in detail, both partial- and general-equilibrium models incorporate assumptions about land availability and distribution, crop yield, and underlying ethanol market drivers. Needless to say, different combinations of these assumptions lead to different estimates of iLUC and crop exports. Consequently, model-based estimates of the potential iLUC impacts of corn use for ethanol production in the USA span a wide range of 0.09 to 0.73 ha per 1000 gallons.[5,8–11] Thus, there is a continuing need for research to clarify the iLUC impacts of biofuel production.

In this paper, we apply a decomposition approach to estimate contributions from several major processes to the supply of corn for ethanol production in the USA from 2001 to 2009. By estimating the contributions of these underlying processes, it becomes possible to evaluate the assumptions often used in simulating the iLUC impacts of corn-ethanol production against real data. More importantly, lessons from the empirical data will be useful to support future analyses of the land-use-change implications of biofuels. The findings are also important for cellulosic ethanol and broader biomass programs because some of the potential feedstock sources have similar land-competition issues.

The rest of the paper provides an overview of the empirical corn market and cropland data used in this study, presents the decomposition methodology and its application to the data on corn supply and use, discusses the implications for estimation of the indirect effects of corn use for ethanol production in the USA, and offers conclusions.

US corn-supply, corn-use, and cropland data

The analysis in this study employed data on corn supply, distribution, and harvested area for various crops spanning the period from 1980 to 2009. Most of these data are from the Production, Supply, and Distribution (PSD) database of the United States Department of Agriculture.[12] Data on the use of corn for ethanol production are from the Feed Grains database.[13] Total cropland area data for 1980 to 2009 are also from USDA sources.‡[14,15]

Corn-production, stocks, land-use, and yield data

Figure 2 illustrates the data on corn production in the USA from 1980 to 2009. The data show that in the 20-year period from 1980 to 2000, annual production fluctuated between 150 million tons and 250 million tons. Since 2000, the production of corn has climbed by almost 50% from 250 million tons to just below 350 million tons. Specifically, corn production increased in 2003, 2004, 2007, and 2009. In addition, the data on net withdrawals of stocks in Fig. 2 show that corn inventories were more stable between 1990 and 2000 compared to the wide fluctuations in the preceding decade. In turn, inventories have played an even smaller role in supply–demand balancing between 2000 and 2009 compared with the period from 1990 to 2000. Overall, withdrawals from stock between 2000 and 2009 represented from 2 to 5% of total domestic corn consumption and exports, whereas

* The Food and Agricultural Policy Research Institute (FAPRI) model is a global econometric agricultural model consisting of multiple crop and livestock modules. FASOM is a US forestry and agricultural model.

† Global Trade Analysis Project (GTAP) is a global general equilibrium model.

‡ Total cropland harvested includes row crops and closely sown crops; hay and silage crops; tree fruit, small fruit, berries, and tree nuts; vegetables and melons; and miscellaneous other minor crops.[14]

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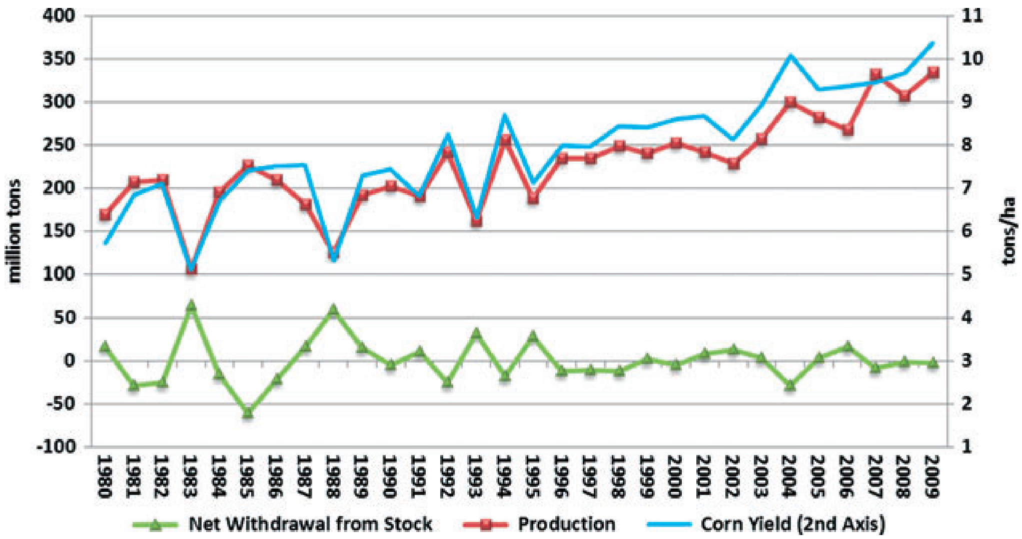

Figure 2. Patterns of corn production, net stock withdrawal and yield in the United States: 1980–2009.

additions to stock in 2004 and 2007 amounted to 11% and 3%, respectively.

Figure 3 shows that total cropland harvested in the USA fluctuated significantly in the 1980s within a range of 116 to 142 million hectares but has remained relatively stable since 1990. The total harvested area stayed between 120 and 126 million hectares from 1990 to 1995 and rose to about 130 million hectares in 1997. The range was 123 and 128 million hectares from 1998 to 2009, except in 2002 and 2006 when it declined to about 124 million hectares and 123 million hectares, respectively. Figure 3 also shows that the trend in area of corn harvested since 1980 is generally similar to that for total harvested cropland. In the most recent decade, the area of corn harvested increased only slightly from 2001 to

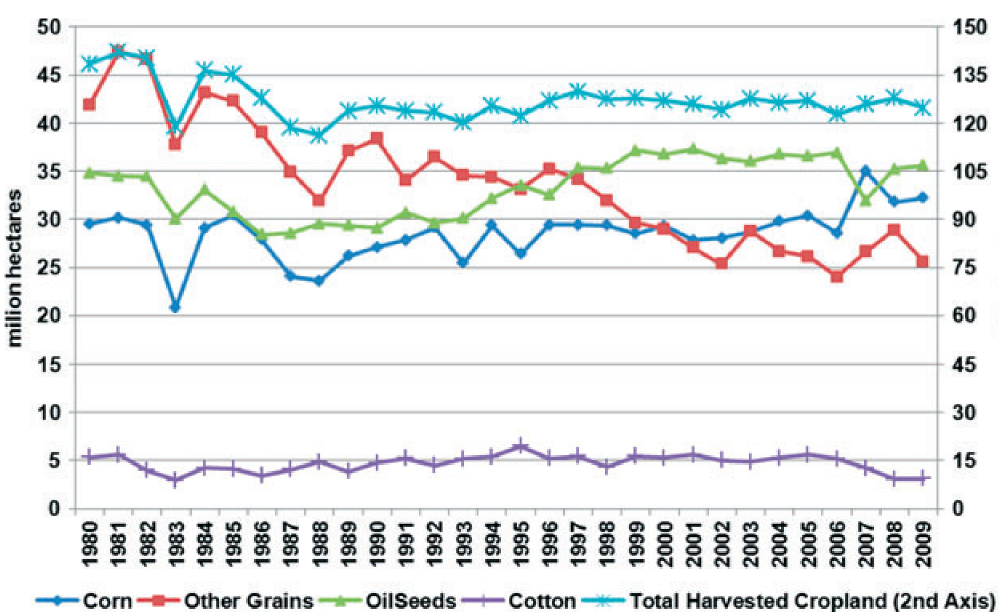

Figure 3. Cropland area harvested for major crops and total cropland harvested in the United States: 1980–2009.

2005 and returned to its 2001 level in 2006, but showed a large jump in 2007. By 2009, about two-thirds of the increase in area between 2005 and 2007 had returned to other crops. Figure 3 suggests that most of the changes in corn land occurred within the grains category, with land under other grains declining between 2003 and 2006. Land under oilseeds remained largely flat from 1997 to 2006 but dropped in 2007 in conjunction with the jump in corn acreage in the same year. However, land under oilseeds rebounded in 2008 and continued to grow in 2009, recouping a majority of the 2007 dip in acreage.

The observed changes in corn production since 1980, particularly the almost 100 million-ton increase between 2000 and 2009, contrast sharply with the relatively stable level of corn and total cropland harvested in the USA during this period. As Fig. 2 shows, corn yield and production tend to move together. Thus, recent large increases in corn production have been in large part from increases in corn yield. Figure 2 shows that corn yield has being growing almost steadily since 1995. In the 15-year period from 1980 to 1995, corn yield increased by a little less than 20% but grew by more than 45% between 1995 and 2009. Several factors are responsible for the observed yield increases. For example, favorable weather conditions in 2003 and 2004 after a significant drought-induced crop failure in 2002[14] partly accounted for the jump in corn yields and production during these years. Similarly, increases in corn prices since 2003 would have enabled farmers to employ high-yield production inputs that are generally too costly at lower prices. Higher corn prices are also likely to have encouraged farmers to switch crops so that more productive lands are used for corn production. Other potential intensification measures that may have contributed to yield increases include changes in rotation cycles and increases in double cropping. Studies suggest that a combination of these factors account for the changes in corn yield.[16,17]

Corn-utilization data

The allocation of corn supply to different uses in the USA from 1980 to 2009 is illustrated in Fig. 4 and shows that: (i) corn allocations to fuel (ethanol) production and for other food, seed, and industrial (OFSI) purposes were small relative to total supply, with a slow but stable growth pattern from 1980 to 2000, while corn use for feed and residuals was the largest allocation; (ii) corn used for ethanol increased rapidly from about 18 million tons in 2001 to about 109 million tons in 2009; (iii) net exports of corn are characterized by substantial fluctuations, ranging from 24 to 60 million tons during the period from 1980 to 2000, but increased almost steadily between 2002 and 2007. Net exports of corn from the USA

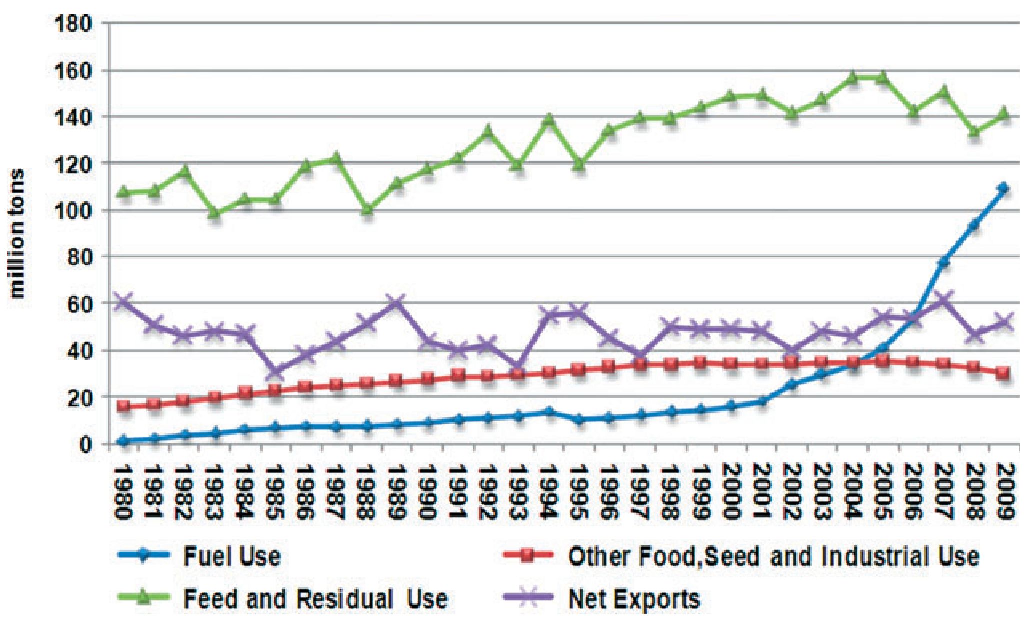

Figure 4. Patterns of corn uses in the United States: 1980–2009.

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increased from 40 million tons in 2002 to about 60 million tons in 2007 before declining to around 53 million tons by 2009. The level of corn export in 2007 has been seen at only two other times from 1980 to 2009 (i.e. 1980 and 1989).

The pattern of feed and residual uses of corn between 1988 and 2009 is notable. Corn uses for feed and residual purposes expanded almost steadily from 100 million tons in 1988 to about 155 million tons in 2004, with only three years of decreases (1993, 1995, and 2002). In contrast, since 2003, the trend of corn use for feed and residual purposes has being declining. Thus, from 2004 to 2009, corn uses for feed and residual purposes decreased by 15 million tons. An evaluation of the data in Fig. 4 in percentages provides further clarification of the changes in corn allocations from 1980 to 2009. [See the Supporting Online Material (SOM).] The distribution of corn among different uses was largely stable from 1980 to 2000, with fluctuations mainly in the share of exports and in feed/residual uses. Since 2001, the share of corn used for ethanol has increased from about 7% of the total corn supply to 33% in 2009. During the same period, the share of OFSI declined from 14% to 9%, while the share of feed and residual uses declined from 60% to 42%. In contrast, the share of exports remained largely stable at between 17% and 19% through 2007, declining to 15% and 16% in 2008 and 2009, respectively.

Decomposition of corn used for ethanol production in the USA

We employ an index decomposition analysis (IDA) method to allocate changes in the amount of corn used for ethanol in the USA to the contributing processes illustrated in Fig. 1, including changes in domestic corn uses, net exports, corn yield, and land use. IDA is a comparative statics technique to estimate the contribution of individual factors or groups of factors to the change in an aggregate variable, if all other factors are held constant.[§18] IDA analysis can be performed either in additive or multiplicative form. In the additive form, the aggregate variable change is the sum of the component contributions, but is the product of the contributions under the multiplicative form. The additive approach is used in this study because its results are easier to interpret than with the multiplicative form.

The Type I Logarithmic Mean Divisia Index (LMDI I) formulation has been recommended for IDA based on an extensive review.[20] For an aggregate variable, *y*, with $i = 1 \ldots n$ contributing factors, $x_1, x_2, \ldots x_n$, and a general functional form:

$$y(x_1, x_2, \ldots x_n) = x_1 * x_2 * \ldots * x_n = \prod_{i=1}^{n} x_i, \tag{1}$$

The LMDI I decomposition of the change in *y* between time *to* and *t1*, Δy, is given by the expression:

$$\Delta y = \sum_{i=1}^{n} \left(\frac{(y_{t1} - y_{t0})}{ln\left(\frac{y_{t1}}{y_{t0}}\right)} \right) ln\left(\frac{x_{i,t1}}{x_{i,t0}}\right) = \sum_{i=1}^{n} \Delta y \frac{g_{xi}}{g_y}, \tag{2}$$

where g_{xi} and g_y are the logarithmic growth rate of x_i and *y*, respectively.

The LMDI I technique was used to decompose changes in the amount of corn used for ethanol production on the basis of a chained relationship that captures the main processes in corn supply and allocation illustrated in Fig. 1. This relationship is specified as

$$Q_{ce} = \left(\frac{Q_{ce}}{Q_{ffsi}}\right)\left(\frac{Q_{ffsi}}{Q_{dom}}\right)\left(\frac{Q_{dom}}{Q_{sup}}\right)\left(\frac{Q_{sup}}{Q_{prd}}\right) Q_{prd} \tag{3a}$$

and

$$Q_{prd} = Y_{corn}\left(\frac{A_{corn}}{A_{cgrn}}\right)\left(\frac{A_{cgrn}}{A_{grn}}\right)\left(\frac{A_{grn}}{A_{grn+oilsd}}\right)\left(\frac{A_{grn+oilsd}}{A_{all}}\right) A_{all}, \tag{3b}$$

where:

Q_{ce} = Annual use of corn for ethanol production (million tons)

Q_{ffsi} = Annual use of corn for food, fuel, seed, and industrial purposes (FFSI; million tons)

Q_{dom} = Annual total domestic corn consumption (million tons)

Q_{prd} = Annual total corn production (million tons)

Q_{sup} = Annual total corn supply (i.e. production + imports + beginning stock) (million tons)

Y_{corn} = Annual corn yield (tons/ha)

§ The IDA is closely related to another decomposition methodology known as Structural Decomposition Analysis (SDA) and differs mainly in the type of data for which it is appropriate. The SDA approach is useful for decomposing changes based on economic input-output tables, while the IDA approach is applicable to more aggregate time series.[19] The underlying computations are essentially the same.

A_{corn} = Annual corn harvested area (million ha)
A_{cgrn} = Annual coarse-grain harvested area (million ha)
A_{grn} = Annual all grain harvested area** (million ha)
$A_{gn+oilsd}$ = Annual all grain plus oilseed†† harvested area (million ha)
A_{all} = Annual total harvested cropland area (million ha)

Equation (3b) was substituted into Eqn (3a) for the computations. The resulting relationship is an apt description of the physical process of corn supply and distribution, and of specifications in models that have been used to evaluate the indirect effects of corn-ethanol production. This relationship was applied to the data from 1980 to 2009, and zero and negative values are avoided because the above variables are positive throughout the horizon. The factors in the decomposition analysis are represented by the multiplicative terms in Eqns (3a) and (3b) which are described below [See the SOM for a more detailed description of the IDA method and the above relationship]:

Q_{ce}/Q_{ffsi}: This factor captures changes in the distribution of a given level of corn used for FFSI between corn ethanol and other FFSI uses. If corn use for ethanol production expanded at a faster rate than other FFSI uses, then the contribution of this factor would be expected to increase, and vice versa.

Q_{ffsi}/Q_{dom}: This factor is similar to the above one in that it captures changes in the distribution of domestic corn consumption between FFSI and other domestic uses, namely food and residual uses. If FFSI expanded at a faster rate than food and residual uses, the contribution of this factor to corn used for ethanol would increase, and vice versa.

Q_{dom}/Q_{sup}: This factor represents the share of domestic consumption in total US corn supply and is the main measure of corn diversion from export markets for ethanol purposes in this study. The contribution of this factor to corn-ethanol production would be expected to increase, and judged to divert exports to domestic markets, under two conditions: (i) if corn exports were reduced while corn used for ethanol production increased and (ii) if corn used for ethanol production were met by increased supply but exports did not grow at the same rate as supply.

Q_{sup}/Q_{prd}: This factor measures the relative contribution of new production to the total supply of corn and therefore captures the role of beginning stock and imports (the latter is quite negligible in the case of the USA at less than 0.5 million tons).

Y_{corn}: This factor represents the contribution of corn yield to corn used for ethanol through the change in corn production.

A_{corn}/A_{cgrn}: This factor represents the ratio of corn harvested area to total coarse grains harvested area and captures the effect of land transfers among coarse grains in corn used for ethanol through the change in corn production.

A_{cgrn}/A_{grn}: This factor captures the effect of land competition between coarse grains and other grains in corn used for ethanol through the change in corn production.

$A_{grn}/A_{grn+oilsd}$: This factor captures the effect of land competition between grains and oilseeds in corn used for ethanol through the change in corn production.

$A_{all}/A_{grn+oilsd}$: This factor captures the effect of land competition between aggregate grains/oilseeds area and other crops in corn used for ethanol through the change in corn production.

A_{all}: This factor reflects the role of total cropland harvested in corn used for ethanol through the change in corn production.

Contributions of supply and distribution factors to changes in corn used for ethanol

Table 1 shows the decomposition of changes in corn used for ethanol production from 2001 to 2009 based on Eqns (3a) and (3b). [See Table 1 of the SOM for the full decomposition results for 1980 to 2009.] Figure 5 provides a summary of the results for 2001 to 2009. Most of the changes in corn used for ethanol from 1980 through 2009 can be attributed to changes in Q_{ce}/Q_{ffsi} and Q_{ffsi}/Q_{dom}, which are both adjustments in the distribution of total domestic corn use. In contrast, contributions from the supply factors, Q_{dom}/Q_{sup}, Q_{sup}/Q_{prd}, and Q_{prd}, are almost equally negative and positive over the period. The contributions of these three factors are highly variable; suggesting that ethanol production had

** Grains include corn, barley, oats, rye, and sorghum (coarse grains), wheat, and milled rice (other grains).

†† Oilseeds include soybean, cottonseed, peanut, rapeseed, and sunflowerseed.

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Table 1. Decomposition analysis estimates of contributions from supply and distribution factors to changes in corn used for ethanol production from 2001 to 2009 (million tons).

	Share of fuel uses in all FFSI uses	Share of FFSI uses in domestic consumption	Share of domestic consumption in total supply	Ratio of total supply of corn to production	Production	Total change in corn use for ethanol
2001	1.23	0.52	0.57	0.38	–0.72	1.99
2002	4.48	2.89	1.60	–0.38	–1.24	7.36
2003	2.16	0.77	–0.10	–1.69	3.23	4.37
2004	2.14	–0.07	–2.30	–0.78	4.97	3.95
2005	3.26	2.65	–0.11	3.56	–2.24	7.12
2006	5.71	7.67	2.37	–0.12	–2.52	13.11
2007	8.77	6.66	–0.78	–4.90	13.86	23.62
2008	5.60	11.19	2.99	2.58	–6.42	15.94
2009	5.79	2.21	0.01	–0.66	8.49	15.83

little influence on their major determinants. A calculation of the correlation coefficients between the change in corn used for ethanol and the factor contributions supports the above observations. For the entire period of 1981 to 2009, the magnitudes of the correlation coefficients for the two distribution factors are 97% and 82%, whereas the correlation coefficients for the three supply factors are 20, 26, and 42%, respectively. These coefficients are similar when calculated for 2001 to 2009. For 1981 to 2000, the coefficient for the Q_{ce}/Q_{ffsi} factor is almost 99%, and that for the production factor, Q_{prd},

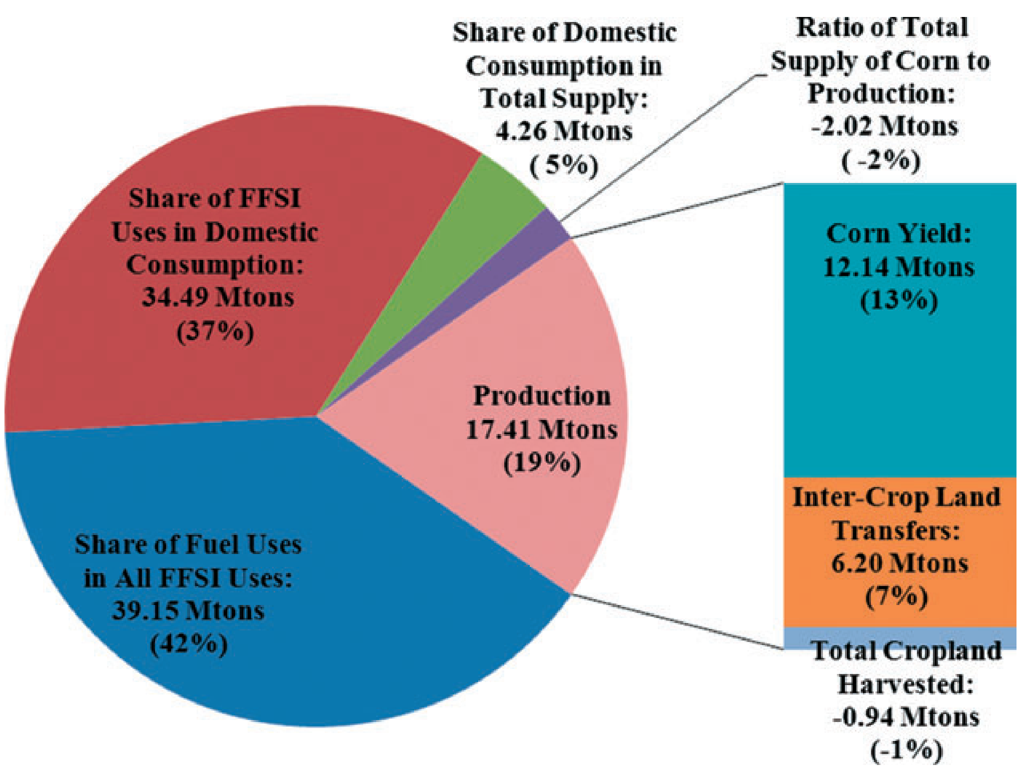

Figure 5. Summary of decomposition analysis estimates of contributions by supply and allocation factors to changes in corn used for ethanol production from 2001 to 2009 (note that the percentages add to more than 100% because of rounding).

is 55%. The coefficients for the remaining factors were around 40%.

Most of the correlation coefficients are positive during the period of large increases in corn used for ethanol production from 2001 to 2009, but only those for the domestic corn-use allocation factors, Q_{ce}/Q_{ffsi} and Q_{ffsi}/Q_{dom}, and production, Q_{prd}, are greater than 25%. The factor representing the share of domestic consumption in total supply, Q_{dom}/Q_{sup}, is positively correlated with corn used for ethanol production for 2001 to 2009, but its correlation coefficient is only 20%. Among the three supply factors, only production was positively correlated with changes in corn used for ethanol production during 1981 to 2000. These observations mean that changes in corn use for ethanol production were more correlated with changes in production and allocation of domestic consumption in favor of ethanol than with diversion of exports. This combination of changes enabled the share of domestic consumption in the total supply of corn (and the export share) to remain stable as farmers increased production to satisfy both domestic and export demands.

As seen in Table 1 and Fig. 5, from 2001 through 2009 domestic corn-use reallocations accounted for 79% of the roughly 93 million-ton increase in corn used for ethanol production, while changes in corn production accounted for about 19%. The factor representing changes in the share of domestic corn use in total supply, Q_{dom}/Q_{sup}, accounted for only 5% or a little more than 4 million tons from 2001 to 2009. In addition, the net contribution of changes in the ratio of total supply to total production is only −2%. Thus, while the latter factor contributed 50% of the increase in corn used for ethanol in 2005 (drawing down stock built up from a bumper harvest in 2004), withdrawals from stock were not a source of corn for ethanol production when looking at net contributions over the entire period.

Contributions of changes in yield and area harvested to corn used for ethanol

When the production contributions are disaggregated into yield and harvested-area factors, the results, though only directly applicable to the use of corn for ethanol production, nevertheless illustrate the important role of yield in recent increases in corn production in the USA. [See Table 2 of the SOM for the full decomposition results.] Yield changes dominate both negative and positive production contributions to corn used for ethanol, except for a few years. Thus, the large contributions from production in 2003, 2004, and 2009 were mainly produced by yield changes. Changes in total cropland area (A_{all} in 2003), share of corn area in harvested coarse-grain area (A_{corn}/A_{cgrn} in 2004 and 2009), and share of coarse-grain area in harvested area of all grain (A_{cgrn}/A_{grn} in 2004 and 2009) accounted for most of the remaining production contributions. In contrast, the large contribution from production in 2007 was largely produced by harvested-area factors (A_{all}, $A_{grn}/A_{grn+oilsd}$ and A_{cgrn}/A_{grn}). More importantly, only in 2007 was the increase in corn used for ethanol production shown to be associated with a substantial decrease in land under other crops (mainly oilseeds). In that year, the contribution from $A_{grn}/A_{grn+oilsd}$ was estimated at 7.4 million tons (about half of the production contribution to corn used for ethanol), whereas changes in total harvested area, A_{all}, contributed about 4.5 million tons. As already highlighted, record-level corn exports were also observed in 2007, so the reduction in land under oilseeds in 2007 was accompanied by increases in corn exports as well as corn-ethanol production.

The net contribution from changes in corn production from 2001 to 2009 amounted to about 17.5 million tons, 12 million tons of which resulted from corn yield changes. This yield contribution represents 13% of the increase in corn use for ethanol production during the period or almost 70% of the production contribution. The remaining contributions were 0.26 million tons from $A_{grn}/A_{grn+oilsd}$, 1.3 million tons from $A_{grn+oilsd}/A_{all}$, and a negative 0.9 million tons from changes in total harvested cropland, A_{all}. The largest yield contributions were in 2003, 2004, and 2009, three of the four years in which production changes contributed most of the increase in corn used for ethanol (the other being 2007). The contributions of yield change in the decomposition results follow directly from its large share of the increases in US corn production since 2001, as already highlighted in the discussion of Fig. 2. In 2003, 2004, and 2009 the area of corn harvested increased by about 2.3%, 3.8%, and 1.4%, while yield jumped by 10%, 13%, and 7%, respectively. In contrast, contributions from changes in the share of domestic consumption in the total supply of corn were negative in these three years, implying that a larger proportion of the production increases were used for purposes other than domestic consumption (i.e. exports and additions to stock).

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Discussion

Implications for the indirect effects of recent increases in US corn-ethanol production

An overview of the empirical data suggests that changes in domestic corn-use allocations and production growth were the most important sources of the increase in corn used for ethanol production from 2001 to 2009. The share of feed and residual uses in total corn supply declined by 18%, while that of other food, seed, and industrial uses declined by 5%. This aggregate 23% decline is comparable to the 26% increase in the share of corn used for ethanol between 2001 and 2009. The declining trend in corn used for feed and residual purposes since 2005, which contrasts with its increasing trend from 1988 to 2004, provides additional evidence that adjustments in domestic uses were the largest source of corn for ethanol production. The data also showed that corn exports increased during most of the period from 2001 to 2009. The sustained increase in the trend of corn exports from 2002 to 2007 is comparable to only one other period, 1985 to 1989, during the last three decades. Although stocks played a crucial supply–demand balancing role from year to year, net withdrawals were close to zero during this period.

The systematic decomposition analysis to allocate increases in corn used for ethanol to changes in corn supply and distribution factors reinforces the above observations. The analysis shows that 79% of the net increase in corn used for ethanol between 2001 and 2009 can be attributed to adjustments in the distribution of total domestic corn use. Changes in corn production were shown to account for another 19%, whereas the stock-change contribution was a net −2% over the period. The balance of 5% was from increases in the domestic share of total corn supply, amounting to about only 4 million tons during the 9-year period. Additional information as to whether increases in the share of domestic corn use were at the expense of exports can be gleaned by examining the net contributions of factors representing production (Q_{prd}) and beginning stock (Q_{sup}/Q_{prd}) against the domestic-share factor contribution. The sum of contributions from Q_{sup}/Q_{prd} and Q_{prd} were negative and large enough to offset positive contributions from the domestic-share factor in three of four years, 2002, 2006, and 2008. This offset suggests that increases in the domestic-share contributions resulted from lower total supply in those years. A clear case for diversion of exports to domestic markets can only be demonstrated if positive contributions from the domestic-share factor are accompanied by either zero or positive changes in the contributions of supply factors. Figure 3 confirms that corn production dipped in all four years with positive domestic-share factor contributions.

The first full year of the recent global recession, 2008, is of particular interest. As noted earlier, the data suggested that the decline in corn production for 2008 was partly caused by the movement of land to other crops. Information from the *USDA Newsroom* during the planting season of 2008 summarized the expected drop in corn acreage as follows:

> **USDA expects corn acres to drop in 2008: WASHINGTON, Mar. 31, 2008** On the heels of last year's record-high corn production, US farmers intend to plant 8% fewer corn acres in 2008, according to the *Prospective Plantings* report released today by the US Department of Agriculture's National Agricultural Statistics Service (NASS). Producers plan to plant 86 million acres of corn this year. While 7.6 million acres less than 2007, this would still be the second-largest area since 1949. The outlook for corn prices remains strong, thanks to increasing ethanol production and other factors. Still, favorable prices for other crops, along with crop rotation considerations and high corn input costs, are motivating some farmers to switch from corn.

Although the rest of the world (ROW) increased planted corn acreage in 2008, the effects of the recession seem to be reflected in the behavior of both corn prices and exports. Corn prices plunged in mid-2008 along with other commodity prices as the recession began to take its toll on the global economy.[21] Thus, by the US harvesting season, October/November, corn had lost more than $100/ton since its February 2008 peak price of $287/ton. This large reduction in price, even with significant reductions in US production, is the outcome of a combination of commodity demand destruction accompanying a recession, incorrect speculation on commodity prices, and likely excess production by the ROW. Given the lag between corn planting and harvesting the last two factors can also be interpreted as indirect effects of the global economic recession resulting from unfulfilled demand expectations. Thus, corn production by the ROW plunged by 35 million tons in 2009, while production in the USA rose by about 26 million tons.[22] Although exports of corn by the USA rebounded in 2009, the increase was only about 5 million tons, compared with a decline of almost 15 million tons in 2008.

Contributions of the domestic-share factor to corn used for ethanol between 2001 and 2009 could be interpreted as diversions from exports. The 5% net contribution over the period would amount to an annual average of less than 0.5 million tons. If reductions in corn exports in 2008 and 2009 were attributed to the recent global recession, given the above observations, the estimate for 2001 to 2007 drops to a little more than 1 million tons, or less than 0.2 million tons annually. This represents about 0.4% of the average annual exports of corn by the USA during the same period. However, given that our analysis is confined to the USA side of the market and that commodity markets in general experienced dramatic changes during 2008 and 2009, it is impossible to rule out alternative explanations of these global corn market changes.

The decomposition results also show that about 70% of the 19% net contribution from the corn production factor during 2001 to 2009 can be attributed to yield changes. Overall, contributions from land factors were shown to vary significantly from year to year. Contributions from total harvested cropland were substantial in 2003 and 2007, while the share of corn in the harvested coarse-grain area and that of coarse-grain in the harvested all-grain area were the main land-related factors in 2004, 2009, and to a lesser extent in other years. Contributions from changes in the grain share of the aggregate grain–oilseeds harvested area is of special interest because the displacement of other export crops is one of the main assumptions underlying estimates of iLUC from corn-ethanol production. The net contribution of this factor from 2001 to 2009, amounting to only 0.26 million tons, was dominated by its 2007 contribution of 7.4 million tons. The net contribution during the remaining years, 2001 to 2006, 2008 and 2009, was a negative 7 million tons.

The above discussion means that the diversion of corn exports contributed little to supplying the corn used for ethanol production from 2001 through 2009, even if the recession that began in late 2007 were not responsible for declines in exports in 2008 and 2009. Similarly, the diversion of cropland to corn production is shown not to contribute significantly to the corn used for ethanol production over the period, with the exception of 2007, during which both exports and domestic uses of corn increased significantly. Most of the changes in corn used for ethanol production were met by the domestic market mainly through the reallocation of the domestic portion of total corn supply in favor of ethanol and increases in the production of corn.

Two additional questions remain: How were the changes in other domestic uses of corn accounted for in the affected sectors? How did other crop markets change in view of the increases in corn used for ethanol production during the past decade? A summary of the available data provides some insights into these questions.

The role of corn-ethanol byproducts

The 23% reduction in the share of domestic uses of corn in total supply, other than for corn-ethanol production, occurred mainly in the feed and residual uses category. However, this did not lead to large reductions in livestock production activities partly because about one-third of the corn used for ethanol production is returned as a byproduct known as distiller's grains with solubles (DGS). Wet or dry DGS is a high-protein substitute for corn, soybean, or other grain products in cattle, dairy, swine, and other livestock feed. The estimate of the DGS production in 2009 is estimated at about 38 million tons, which is more than twice the 15 million-ton decline in feed and residual corn use since 2005.[23] As seen in Fig. 4, the direct use of corn for feed and residual purposes in 2009 was the same as its 2002 level, despite rapid economic growth between 2002 and 2007. Thus, DGS can be reasonably assumed to have made up for a large portion of the absolute decrease in the level of corn use for feed and residual purposes, as well as for increases that would have invariably occurred during those years. In addition, exports of DGS grew from less than 1 million tons in 2004 to more than 8 million tons in 2009, adding to the steady growth in corn exports by the USA during the period, and replacing corn and other crops used for feed in the receiving nations. In addition, there is some evidence that the use of DGS in livestock feed improves feed efficiency relative to corn and soybean.[24]

Changes in production and use of other crops

A look at the data on production, net stock withdrawals, domestic use, and net exports of non-corn grain crops and oilseeds suggest little use of these crops to compensate for decreases in domestic uses of corn for food, feed, and residual purposes. [See Figures D.2 and D.3 of the SOM for illustrations of the data.] If one uses the 5-year period from 1996 to 2000 for comparison, the pattern of each of these variables did not change dramatically during the period from 2001 to 2009. From 1996 to 2002, annual production of non-corn grains declined from 100 million tons to less than 70 million tons but peaked at about 93 million tons in 2008. The data also show that the production of these crops increased in two of the same years when large increases in corn production were observed in Fig. 2 (2003 and 2007). Similarly, exports were strong in those high production years. In contrast to exports, domestic consumption and net stock withdrawals were relatively flat from 2002 to 2007.

The production of oilseeds increased in 2004, which is consistent with the decrease in non-corn grain crop production in that year. Oilseed production declined in 2003 and 2007, but, unlike grains, remained at an elevated level from 2004 through 2006. Production returned to the 2006 level in 2009 after a sharp dip in 2007. Net stock withdrawals of oilseeds were also close to zero between 2001 and 2007, whereas exports of oilseed crops increased steadily after 2003, except for a slight dip in 2005. Compared to 2001, oilseed exports were up by more than 30% in 2009. As with non-corn grain crops, the domestic consumption of oilseeds remained largely flat between 2001 and 2009.

The above production and export data reinforce the observation that harvested cropland area for all major crops grown in the USA did not change dramatically in response to the large increases in corn used for ethanol between 2001 and 2009. In 2007, when oilseed production declined as grain production increased, exports of oilseeds continued to increase. The impact of the decline in production and increase in export of oilseeds during that year is reflected in the jump in net stock withdrawals.

Conclusions

The analysis in this paper provides a first-order empirical assessment of some of the key assumptions underlying estimates of the indirect impacts of US corn-ethanol production with data from 1980 to 2009. An overview of the empirical corn market data and an index decomposition analysis of corn used for ethanol production provide little support for two fundamental iLUC modeling assumptions: (i) that increases in corn used for ethanol production lead to significant diversions of US corn exports, and (ii) that increases in corn used for ethanol production lead to displacement of land under other crops and their exports. Regarding exports, our analysis estimates a diversion of 0.5 million tons per year to corn used for ethanol production from increases in the domestic share of total supply (or a decline in the share of export and ending stocks) between 2000 and 2009. The estimate drops to 0.2 million tons when the recession years 2008 and 2009 are excluded. This amount represents between 0.4% and 1% of average annual corn exports during these years. The results also show that significant land diversion from crops other than grains, particularly oilseeds, was limited to one year during the period of study (2007), but oilseed exports increased steadily from 2003 to 2009, except in 2005.

These results suggest that the most crucial factors in supplying corn for ethanol production in the USA during the past decade are re-distributions of domestic corn uses and increases in corn production, with yield change representing almost 70% of the production contribution. The empirical data also show that potential secondary effects from adjustments in domestic use do not lead to significant diversions of land from other crops or of crops from export markets. These findings mean that domestic adjustments within the corn and other agricultural product markets absorbed most of the impacts from the use of corn for ethanol production during the past decade.

Overall, the results of this analysis suggest that the domestic and international iLUC implications of US corn-ethanol production over the last decade are lower than what would be estimated under the usual assumptions of significant displacement of corn exports and other crops by ethanol. Given that the USA already produces 85% of corn ethanol allowed under current legislations, these implications may be expected to hold for the current RFS legislation. Although this study is based on historical data during a period of phenomenal growth in ethanol output it is not predictive. However, the results imply that estimates of future indirect effects (for conventional or advanced biofuels) need to better reflect the complex interactions among the drivers of land use, crop production, crop exports, and biofuel policies. In addition, the study does not provide a full causal analysis to explain the reasons behind changes in the variables contributing to the corn used for ethanol production. Further research is needed to gather and apply empirical evidence to improve the characterization of global land use and market responses to policies like EISA. A useful extension of the decomposition analysis presented in this paper would be its application to the global demand/production of corn and other crops to evaluate the factors behind recent surges in global market demand/production, and the effects of changes in US crop production. This and other extensions are reserved for future work.

Supporting information

Supporting information can be found in the online version of this article.

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