Environmental Science & Technology

Article

pubs.acs.org/est

Corn Ethanol Production, Food Exports, and Indirect Land Use Change

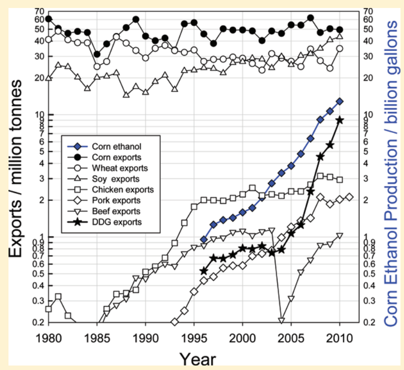
T. J. Wallington,* J. E. Anderson, S. A. Mueller, E. Kolinski Morris, S. L. Winkler, and J. M. Ginder

Systems Analytics and Environmental Sciences Department, Ford Motor Company, Mail Drop RIC-2122, Dearborn, Michigan 48121-2053, United States

O. J. Nielsen

Department of Chemistry, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, Denmark

ABSTRACT: The approximately 100 million tonne per year increase in the use of corn to produce ethanol in the U.S. over the past 10 years, and projections of greater future use, have raised concerns that reduced exports of corn (and other agricultural products) and higher commodity prices would lead to land-use changes and, consequently, negative environmental impacts in other countries. The concerns have been driven by agricultural and trade models, which project that large-scale corn ethanol production leads to substantial decreases in food exports, increases in food prices, and greater deforestation globally. Over the past decade, the increased use of corn for ethanol has been largely matched by the increased corn harvest attributable mainly to increased yields. U.S. exports of corn, wheat, soybeans, pork, chicken, and beef either increased or remained unchanged. Exports of distillers' dry grains (DDG, a coproduct of ethanol production and a valuable animal feed) increased by more than an order of magnitude to 9 million tonnes in 2010. Increased biofuel production may lead to intensification (higher yields) and extensification (more land) of agricultural activities. Intensification and extensification have opposite impacts on land use change. We highlight the lack of information concerning the magnitude of intensification effects and the associated large uncertainties in assessments of the indirect land use change associated with corn ethanol.



■ INTRODUCTION

Concerns related to climate change and energy security combined with a desire to provide support for rural communities has led to a substantial increase in the global production of biofuels. The U.S. production of ethanol increased by an order of magnitude over the past 15 years, reached 13 billion gallons (49 billion liters) in 2010, and grew at 15−20% per year over the last two decades.[1] Most ethanol produced in the U.S. is made from corn sugars. In 1990, the production of ethanol required processing approximately 3% of the corn harvest, but in 2010 that figure was 37%. The U.S. Renewable Fuel Standard calls for the use of 36 billion gallons (136 billion liters) of biofuel by 2022 with a maximum of 15 billion gallons of corn ethanol (more could be produced but it would not count toward meeting the standard). Continued growth in biofuel production is likely, although given the research and development efforts on second-generation biofuels such as cellulosic ethanol, biobutanol, and algae-based fuels, the future contribution of corn ethanol is unclear.

When computed on a gCO_2 equivalent per MJ of fuel produced basis, life-cycle assessments of the greenhouse gas (GHG) emissions associated with corn ethanol use in transportation typically report a modest (approximately 20%) benefit compared to conventional reformulated gasoline.[2−4] It is standard practice in such comparative life cycle analyses to consider only direct effects. However, it has been suggested[5−8] that indirect land-use changes need to be included in life cycle assessments of the environmental impacts of biofuels and that this turns a modest benefit into a large penalty.[9] For example, some have argued[5] that corn ethanol production will reduce food exports from what they would have been without ethanol production leading to deforestation in other nations. The issue of whether it is appropriate to include such indirect effects is controversial[10] and not the focus of the present study.

Recently, Kim and Dale[11] reported the results of an empirical assessment of the evidence for land-use change associated with the production of corn ethanol in the U.S. Kim and Dale[11] found that biofuel production in the U.S. from 2002 to 2007 is not significantly correlated with changes in croplands for corn plus soybean in regions of the world which are U.S. trading partners. Kim and Dale[11] conclude that there was no discernible empirical evidence for indirect land use change associated with corn ethanol production. O'Hare et al.[12] argue that the methodology used by Kim and Dale was flawed because a correlation (or lack thereof) between two factors in a

Received: January 18, 2012
Revised: April 13, 2012
Accepted: April 25, 2012
Published: April 25, 2012

system with many interacting factors can not be used to indicate (or counter-indicate) causation. O'Hare et al. argue that it is not possible to draw any inferences from the empirical data presented by Kim and Dale.[11] Kline et al.[13] commented on the need to use scientific analysis to assess policy effects and specifically to improve assumptions used for modeling.

The issue of indirect land use change associated with biofuel production in general, and corn ethanol production in particular, is of great interest to the scientific, regulatory, and business communities and, as noted above, is highly contentious. Prior to the recent ramp-up of corn ethanol production the discussions of the potential impacts on agricultural exports were by necessity based purely on theoretical evidence gathered using agricultural and trade modeling approaches. Now in 2012, we have an extensive record of agricultural data for the U.S. that includes the past decade in which a very large increase in corn ethanol production occurred. It seems natural to examine the historical trends in agricultural productivity and exports for insight into factors relevant to indirect land use change. Furthermore it seems reasonable to compare and contrast the actual observed behavior of the agricultural/international trade system to expectations based on previous modeling studies.

Our analysis covers the time period up through 2010 and focuses on agricultural productivity, corn ethanol production, and agricultural exports from the U.S. We do not seek to prove, or disprove, the existence of indirect land use change. We highlight the fact that the increased use of corn for ethanol in the U.S. was essentially matched by the increased corn harvest over 2000–2010. Increased yield per acre achieved through genetic improvements/hybrid plant breeding was the major factor[14] and increased acreage was a minor factor in the increased corn harvest. We document that over the past decade: (i) there has been no discernible change in land-use within the U.S., (ii) exports of corn, wheat, soybeans, pork, chicken, and beef have increased or remained unchanged, and (iii) exports of distillers' dry grains have increased by approximately 10 fold.

Whether, or not, there has been any significant indirect land use change associated with corn ethanol production requires modeling studies in which two cases (ethanol production or no ethanol production) are considered. We argue that a minimum requirement of future modeling studies is that in the ethanol production case the models reproduce the historical trends of corn, wheat, soybeans, pork, chicken, beef, and DDG exports over the past 10–15 years. As with all modeling studies, the consistency of model output to experimental observations needs to be examined carefully. Furthermore, the input assumptions need to be critically evaluated in light of the historical record. We argue that future models need to better account for increased yields in the U.S. and the rest of the world resulting from improvements in agricultural technology, which may have been driven by biofuel production in the U.S. This is important because, by definition, such increased yields and additional corn production within the U.S. carry a *zero* land use change burden. Furthermore, increased yields and additional corn production outside the U.S. resulting from improvements in agricultural technology, *if* driven by biofuel production within the U.S., would lead to a *decrease* in land use outside the U.S. and hence a *negative* (favorable) land use change burden. Finally, we note agronomy research and development has a long time frame. It is possible that the recent demand growth for fuel ethanol could engender significant long-term technological dividends (lower costs, higher yields) but that most of the short-term response reflects other yield response factors (more intensive land use, investment in new equipment, moving corn onto best land, increase in soy-corn or corn–corn rotation at expense of other low-yield management systems, weather variability). This is complex and difficult to represent accurately in models.

METHODOLOGY

The United States Department of Agriculture Foreign Agricultural Service (USDA-FAS) maintains a detailed online database[15] for the global production, import, and export of agricultural commodities. Data on the USDA-FAS Web site extend back to 1960, are updated on a monthly basis, and can be used to investigate trends in U.S. exports or imports of agricultural products. The United States Energy Information Administration (EIA) provides a monthly review of energy statistics[1] including the production of fuel ethanol. Fuel ethanol in the U.S. is produced from corn with one bushel (0.035 m^3) producing approximately 2.8 gallons (10.6 L) of ethanol and a significant amount of residual protein-rich DDG used to feed livestock. [16] Hence, we can use the EIA ethanol production data to estimate the volume of the corn crop used for ethanol production. We use the USDA and EIA data to provide an overview of historical ethanol production and agricultural exports. We compare and contrast the historical record with predictions from models used to investigate indirect land use change.

RESULTS

Figure 1 shows U.S. corn ethanol production and corn, wheat, soy, chicken, and pork exports through 2010.[15] Relative to exports, U.S. imports of these commodities are of minor importance and are not considered here. Whereas ethanol production has increased considerably, there was little, or no,

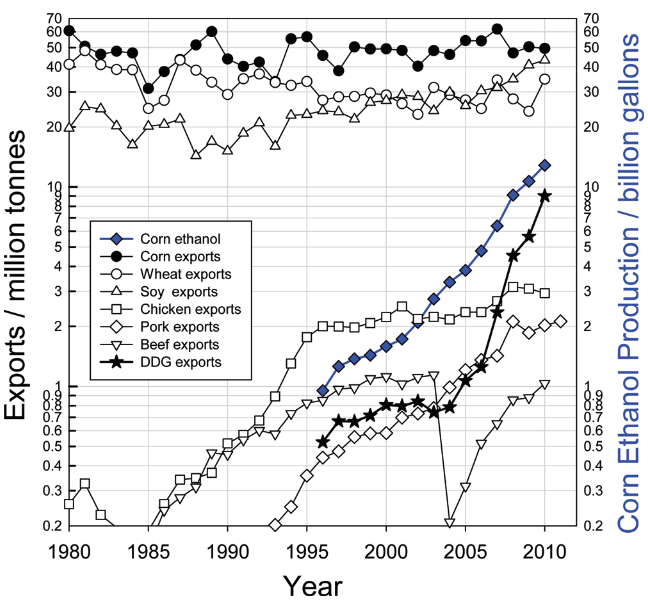


Figure 1. U.S. corn ethanol production (filled blue diamonds, right-hand scale) and exports (left-hand scale) of corn (filled circles), wheat (open circles), soybeans (open triangles), chicken (open squares), pork (open diamonds), beef (inverted open triangles), and distillers' dried grains (DDG, filled stars). Data source: USDA 2011 http://www.fas.usda.gov.

dx.doi.org/10.1021/es300233m | Environ. Sci. Technol. 2012, 46, 6379–6384

discernible change in the exports of corn and wheat over the past decade, and exports of soybeans, chicken, and pork have *increased* significantly. Beef exports in 2010 recovered to their pre-2004 levels after import bans ended. Despite the fact that the amount of corn used to produce ethanol over the period 2000−2010 increased by approximately 100 million tonnes per year, annual corn exports have remained essentially unchanged at approximately 50 million tonnes (Figure 1).

Distiller's dry grains (DDG) are a coproduct of ethanol production and are a valuable animal feed. The nutritional value of DDG as an animal feed is substantial with each tonne displacing approximately 1.2 tonnes of corn.[17] Along with corn ethanol production there has been a large increase (approximately 30 million tonnes[17]) in the production of DDG in the U.S. over the past 10−15 years, and as shown in Figure 1 there has been a large increase in the exports of DDG. The increased DDG exports cause a reduction in the amount of animal feed that would otherwise need to be produced outside the U.S. (or within the U.S. if exporting other animal feeds). A reduction in demand for animal feed produced outside the U.S. if driven by biofuel demand within the U.S. results in a *negative* indirect land use change associated with U.S. corn ethanol production.

Figure 2 shows the annual U.S. corn harvest, exports, and use in ethanol production (calculated assuming 2.8 gallons (10.6 L)

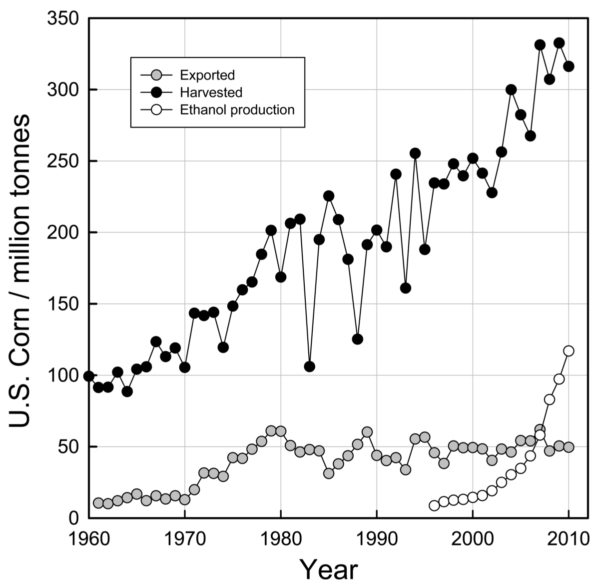


Figure 2. Corn harvested (filled symbols), exported (gray symbols) and used to produce ethanol (open symbols) in the U.S. Data source: USDA 2011 http://www.fas.usda.gov. Drought reduced the corn crop in 1983 and 1988.

of ethanol per bushel and 56 lbs (25 kg) corn per bushel). The corn harvest has steadily trended upward over the past 50 years, increasing at approximately 2% per year. The increased use of corn for ethanol in 2000−2010 was matched by the increased harvest over the same period (many other adjustments occurred simultaneously in the domestic livestock, grain, and feed markets[18]). As seen in Figure 2, corn exports reached a plateau in the 1980s and have remained relatively steady in terms of absolute amounts, declining in terms of the exported share of total production. Of course, one could argue that without the ethanol production exports would have risen, but no such increase in exports took place in the 1980s or 1990s with similar increases in yields in percent terms. Further, wheat export levels and the fraction exported peaked in the 1980s, whereas soybean exports actually increased in the 2000s. Taking the 2000s as the period where corn ethanol production grew most significantly, it is difficult to discern in Figure 1 a negative impact in terms of export trends of corn, soy, wheat, chicken, pork, or beef. The large increase in corn exports in the 1970s was attributable to strong demand in Russia, Japan, and Europe.[19]

As seen from Figure 3, the total area of corn harvested in the past decade increased slightly from that in previous decades

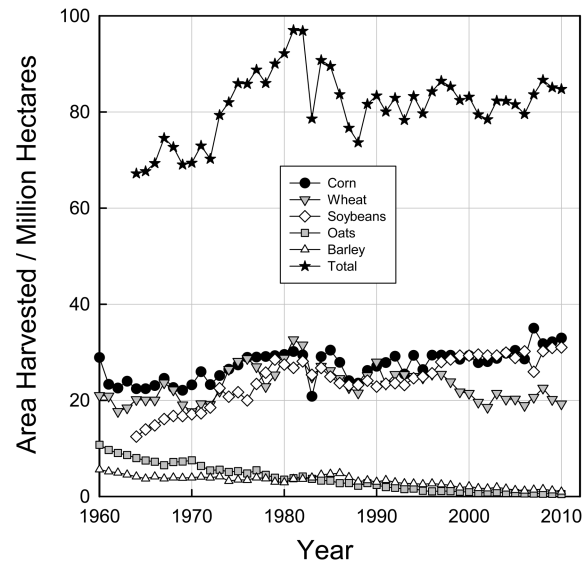


Figure 3. Area harvested in the US for corn (filled circles), wheat (gray triangles), soybeans (open diamonds), oats (gray squares), barley (open triangles), and the total of corn + wheat + soybeans + oats + barley (stars). Data source: USDA 2011 http://www.fas.usda.gov. The land area decrease from 1985 to 1990 reflects changes in the Conservation Reserve Program which went from 5 to 40 million acres over that time frame.

with the area of wheat harvested declining back to levels typical of the 1960s. The harvested area of oats and barley declined in the past decade consistent with the long-term trend over the past 50 years. No trend in the total harvested area of the major cereal crops (corn, soy, wheat, oats, and barley) can be discerned indicating no overall increase in the land devoted to cultivation of grain crops in the U.S. The large increase in the corn harvest over the past decade shown in Figure 2 mainly reflects increases in the yield per acre[18] achieved through genetic improvements/hybrid plant breeding and improved agricultural practices. The use (lb/acre) of nitrogen and phosphorus fertilizer has been stable since 1980.[20] When normalized to yield (lb fertilizer/lb corn), the use of nitrogen, phosphorus, and potash fertilizer has decreased by 35%, 60%, and 50% respectively between 1970 and 2005 for U.S. farms.[4]

Over the last 20 years, there is no significant correlation between corn exports and ethanol production in the U.S. Obviously, correlation (or lack thereof) is not proof of causation (or lack thereof). While the available export and production data for grains, meat, and ethanol do not appear to support the hypothesis that U.S. production of corn ethanol has influenced food (meat and grain) exports up to 2010, neither do they rule it out. It is conceivable that in the time period 2000−2010 the use of corn to make ethanol masked one, or more, effects that would otherwise have led to a substantial increase in corn exports. If such effect(s) are operative, they presumably were either not present or they themselves were masked by other effects in the decades of the 1980s and 1990s when increase corn yields did not lead to increase exports of corn (Figure 2).

■ DISCUSSION

There have been a number of peer reviewed modeling studies,[5,7,9,8] which have reported a range of indirect land use change impacts associated with corn ethanol production in the U.S. Unfortunately, none of the modeling studies make a direct comparison of the results from the model with recent historical data.

Searchinger et al.[5] reported the first, the most cited, and arguably the most influential study of indirect land use changes associated with corn ethanol production. Searchinger et al. used a global agricultural model to estimate the impact on U.S. exports of a 56 billion liter increase (to 112 billion liters) in corn ethanol production by 2016 and predicted declines (compared to what they would have been otherwise) in exports of corn, wheat, soybeans, pork, and chicken by 62%, 31%, 28%, 18%, and 12% respectively or 38.5, 8.1, and 6.4 million tonnes in absolute terms for corn, wheat, and soybeans, respectively. It is clear from Figure 1 that the increase of 43 billion liters (from 6 to 49 billion liters) in corn ethanol production from 2000 to 2010 was not accompanied by a decline in agricultural exports. Searchinger et al. noted that as a result of biofuel production farmers will try to boost yields through improved agricultural practices but that reduced crop rotations and greater reliance on marginal lands would depress yields. Searchinger et al. assumed that historical growth trends in yields would continue but that the positive and negative effects of biofuel production would cancel and that none of the increased yield would be attributable to biofuel production. Many of the assumptions in the study by Searchinger et al. have been questioned by other researchers (e.g., see Wang and Haq[21]).

Hertel et al.[7] conducted a modeling study to assess the indirect land use changes associated with an increase in corn ethanol production from 6.6×10^9 to 56.7×10^9 liters (1.7 to 15×10^9 gallons). The magnitude of the increase in ethanol production modeled by Hertel et al. is very similar to the increase in production from 1.6×10^9 to 13×10^9 gallons, which occurred from 2000 to 2010 as shown in Figure 1. In response to the ethanol expansion, the model employed by Hertel et al.[7] predicts a net increase of 0.41% in the coarse grain yield in the U.S. and a 17% decrease in coarse grain exports from what they would have been in the absence of the ethanol expansion. Corn comprises the vast majority (approximately 91%[7]) of coarse grains and for simplicity we drop the distinction between coarse grains and corn in the rest of this article. As seen from Figure 4, the yield of corn in the U.S. increased by approximately 15% (from approximately 8.5 to 10 tonne hectare^{-1}) in 2000−2010. There is approximately a factor of 40 difference between the 0.41% increase in yield predicted in response to ethanol expansion in the modeling study by Hertel et al.[7] and the approximately 15% increase in the historical record.

In modeling studies such as that reported by Hertel et al, [7] the goal is to separate the impact of increased biofuel production from all other effects in the agricultural system. Given that there are other factors in addition to biofuel production that impact yield increases, it is not surprising that there is a difference between the modeled and observed behavior. However, the magnitude of the difference (approximately 40 fold) is noteworthy given the fact that the major market for the increased corn production over the past 10−20 years has been ethanol production.

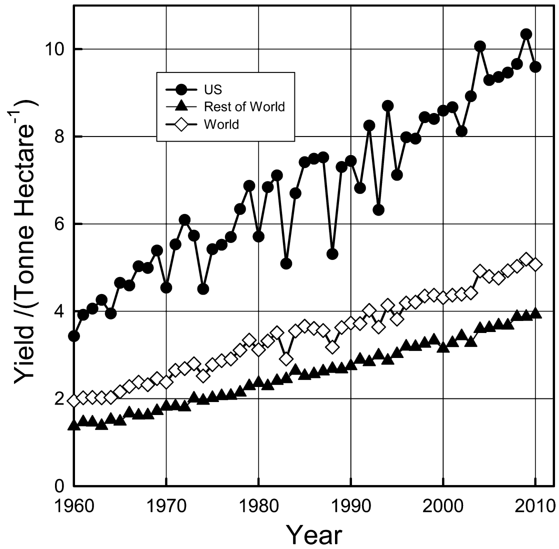


Figure 4. Average yields of corn in the US (circles), the rest of the world (triangles), and the world (open diamonds). Data source: USDA 2011 http://www.fas.usda.gov.

As discussed above, the increase in corn used for ethanol production over the past 10−15 years has been largely matched by the increased harvest over the same period. The increased harvest has been driven mainly by improved yield per acre and, to a lesser extent, by increased acreage. Improvements in yield are attributed to genetic improvements/hybrid plant breeding and to improved crop management in approximately equal measure.[22] Assessing the fraction of the observed yield improvements which is attributable to interest in corn ethanol production driven by energy security, oil price, and biofuel mandates over the past 10−15 years is critical to assessing indirect land use changes. As discussed above, ethanol production has been the major market for the increased corn production. In 2010, the average price for corn was $3.83 per bushel[23] and the value of the additional 100 million tonnes of corn grown for ethanol production was approximately $15 billion.

In simple terms, two arguments can be made for the effect of biofuel production on corn yields. The first argument is that the increased market for corn for ethanol production over the past 10−15 years has had *no* contribution to increased agricultural yields. Some support for this argument could be taken from Figure 4, which shows that there was no discernible change (within the scatter of the data) in the historical trend of increased corn yields within the U.S. over the past 10−15 years. This argument although appealing in its simplicity is not logically sound as there are many factors other than the increased demand for biofuels operating in the complex agricultural system (population growth, dietary trends, economic growth [or lack thereof], energy price fluctuations, international export/import policy changes, cropping practices, weather variability, ...) . Conducting a bivariate analysis and observing a correlation (or lack thereof) between yields and any single factor (e.g., ethanol production) does not prove (or disprove) a causal link. This argument suffers from the same logical deficiency as the argument that the lack of change in corn exports over the past 10−15 years proves that there was no indirect land use change. The second argument is that the increased market for corn for ethanol production over the past 10−15 years has had *some* contribution to agricultural yields. We would argue that, given the additional approximately $15 billion market for corn noted above, basic economic arguments of supply and demand require that there has been some contribution of increased biofuel production to increased agricultural yields. Given the size of the corn ethanol market, the scale of corn ethanol production allowed in RFS2, and the interest in research and development of improved hybrids and improved agronomy practices, it is implausible that ethanol production has had no contribution to increased corn yields.

Assessing the precise contribution of increased biofuel production to increased agricultural yields both in the U.S. and in the rest of the world is a very complex task and beyond the scope of the present study. In the models used by Searchinger et al. and Hertel et al., it was either assumed, or computed, that biofuel production had little or no contribution to an increase in corn yields. There have been few published studies and little discussion in the literature concerning the contribution of increased biofuel production in the U.S. to increased agricultural yields both in the U.S. and potentially in the rest of the world.

To place the magnitude of the importance of a correct accounting of the impact of biofuel production on crop yields into perspective, we can offer the following simple calculations based on the following data over the past 15 years: (i) additional 12 billion gallons of ethanol made annually requiring increased corn use by approximately 100 million tonnes (Figure 1), (ii) approximately 30 million tonne increase in production of DDG (i.e., approximately 30% yield of DDG during processing of corn for ethanol[17]), (iii) 1 tonne of DDG displaces approximately 1.2 tonnes of corn as animal feed,[17] (iv) approximately 30 million hectares harvested for corn in U.S. (Figure 3), (v) approximately 160 million hectares harvested for corn in the world,[15] (vi) observed yield increases in the U.S. and globally were approximately 2 and 1 tonne per hectare (Figure 4). To cover the approximately 100 million tonne increase in corn used for ethanol in the U.S. over the last 15 years and recognizing the 30% yield of DDG would require an approximately 0.4 tonne per hectare $[(100 - (30*1.2))/160 = 0.4]$ increase in the global average corn yield, less than that observed in both the US and globally in the same time period.

If we assume *no* contribution of biofuel production to increased corn yields then, all other factors being equal, there would be indirect land use change associated with increased U.S. corn ethanol production (to compensate for the loss of 100 million tonnes of corn). If we assume that biofuel production was responsible for *all* of the increased corn yields observed in the U.S. but *none* of the increased yield observed in the rest of the world, then, all other factors being equal, there would be a small indirect land use change associated with U.S. corn ethanol (to compensate for the loss of 4 million tonnes of corn equivalent $[100 - (30*1.2) - (30*2)]$). If we assume that biofuel production was responsible for *all* of the increased corn yields observed in the U.S. and *some* of the increased yield observed in the rest of the world, then, all other factors being equal, there would be *negative* indirect land use change associated with U.S. corn ethanol production.

Given the disparity in yields between the U.S. and rest of world shown in Figure 4, there would appear to be substantial opportunities for diffusion of improved agronomy practices (improved soil management, irrigation, fertilizer use, farm machinery) from the U.S. To the extent that improved practices adopted in the rest of the world were developed in the U.S. in response to interest in increased corn ethanol production, there exists a potential for significant impacts, conceivably even leading to negative land-use change impacts in the future. While we do not argue that there is proof that such negative indirect land use changes effects have occurred, we do argue that such effects are plausible and need to be considered in future assessments.

Unlike the situation a decade ago, we now have detailed historical data concerning the production and exports of agricultural products from the U.S. during a time of great expansion of the U.S. biofuel industry. Inspection and analysis of actual historical data provides an important perspective, which is often lacking in discussions of indirect land use change associated with biofuel production. Corn ethanol production has increased by an order of magnitude over the past 15 years but U.S. exports of corn, wheat, soybeans, pork, chicken, and beef have either increased or remained unchanged. Exports of distillers' dry grains (DDG, a coproduct of ethanol production and a valuable animal feed) have increased by more than an order of magnitude. Further work is needed to refine the agricultural models used to estimate indirect land use change so they reproduce the historical record of increased agricultural exports and ethanol production observed over the past 15 years. The contribution of increased ethanol production to increased crop yields and the degree to which agronomy research and development in the U.S. influences crop yields in the rest of the world both now and in the future (agronomy improvements take a long time to diffuse into the global system and require significant capital investment in developing countries) is an important factor which has received little research attention. Given the large gap in crop yields in the U.S. and the rest of the world (Figure 4) there is a significant opportunity for decreasing the indirect land use impacts of biofuel production in the U.S. by intensification (higher yields) rather than extensification (more land) of agricultural activities outside the U.S. The lack of information concerning the magnitude of intensification effects renders assessments of the indirect land use change associated with corn ethanol highly uncertain.

AUTHOR INFORMATION

Corresponding Author

*E-mail: twalling@ford.com, phone 313-390-5574, fax 313-323-1129.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank Maria Grahn (Chalmers University), Chul Kim (Ford), Wulf-Peter Schmidt (Ford), John Sullivan (Argonne National Laboratory), and David Wallington for helpful discussions. We thank the reviewers for comments, which have been very valuable in guiding our thinking on this complex issue and from which we feel the paper has benefited substantially. Whereas this article is believed to contain correct information, Ford Motor Company (Ford) does not expressly or impliedly warrant, nor assume any responsibility, for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, nor represent that its

use would not infringe the rights of third parties. Reference to any commercial product or process does not constitute its endorsement. This article does not provide financial, safety, medical, consumer product, or public policy advice or recommendation. Readers should independently replicate all experiments, calculations, and results. The views and opinions expressed are of the authors and do not necessarily reflect those of Ford. This disclaimer may not be removed, altered, superseded or modified without prior Ford permission.

REFERENCES

(1) U.S. Energy Information Administration, Monthly Energy Review February 2011, http://www.eia.gov/mer/pdf/pages/sec10_7.pdf

(2) Farrell, A. E.; Plevin, R. J.; Turner, B. T.; Jones, A. D.; O'Hare, M.; Kammen, D. M. Ethanol can contribute to energy and environmental goals. *Science* **2006**, *311*, 506−508.

(3) Wang, M.; Wu, M.; Huo, H. Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environ. Res. Lett.* **2007**, *2*, 024001.

(4) Wang, M. Q.; Han, J.; Haq, Z.; Tyner, W. E.; Wua, M.; Elgowainy, A. Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes. *Biomass and Bioenergy* **2011**, *35*, 1885−1896.

(5) Searchinger, T.; Heimlich, R.; Houghton, R. A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgaz, S.; Hayes, D.; Yu, T.-H. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **2008**, *319*, 1238−1240.

(6) Lapola, D. M.; Schaldach, R.; Alcamo, J.; Bondeau, A.; Koch, J.; Koelking, C.; Priess, J. A. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proc. Nat. Acad. Sci. U.S.A.* **2010**, *107*, 3388−3393.

(7) Hertel, T. W.; Golub, A. A.; Jones, A. D.; O'Hare, M.; Plevin, R. J.; Kammen, D. M. *Bioscience* **2010**, *60*, 223−231.

(8) Plevin, R. J.; O'Hare, M.; Jones, A. D.; Torn, M. S.; Gibbs, H. K Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. *Environ. Sci. Technol.* **2010**, *44*, 8015−8021.

(9) Melillo, J. M.; Reilly, J. M.; Kicklighter, D. W.; Gurgel, A. C.; Cronin, T. W.; Palsev, S.; Felzer, B. S.; Wang, X.; Sokolov, A. P.; Schlosser, C. A. *Science* **2009**, *326*, 1397−1399.

(10) Kline, K. L.; Dale, V. H. Biofuels: Effects on land and fire. *Science* **2008**, *321*, 199−200.

(11) Kim, S.; Dale, B. E. Indirect land use change for biofuels: Testing predictions and improving analytical methodologies. *Biomass and Bioenergy* **2011**, *35*, 5235−3240.

(12) O'Hare, M.; Delucchi, M.; Edwards, R.; Fritsche, U.; Gibbs, H.; Hertel, T.; Hill, J.; Kammen, D.; Laborde, D.; Marelle, L.; Mulligan, D.; Plevin, R.; Tyner, W. *Biomass and Bioenergy* **2011**, *35*, 4485−4487.

(13) Kline, K. L.; Oladosu, G. A.; Dale, V. H.; McBride, A. C. Scientific analysis is essential to assess biofuel policy effects: In response to the paper by Kim and Dale on "Indirect landuse change for biofuels: Testing predictions and improving analytical methodologies. *Biomass and Bioenergy* **2011**, *35*, 4488−4491.

(14) Edgerton, M. D. Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant Physiology* **2009**, *149*, 7−13.

(15) United States Department of Agriculture, Foreign Agricultural Service. Production, Supply, and Distribution Online Database, http://www.fas.usda.gov/psdonline/psdQuery.aspx downloaded July 2011.

(16) Mueller, S. M.; Anderson, J. E.; Wallington, T. J. Impact of biofuel production and other supply and demand factors on food price increases in 2008. *Biomass and Bioenergy* **2011**, *35*, 1622−1632.

(17) Arora, S.; Wu, M.; Wang, M. Estimated displaced products and ratios of distillers' co-products from corn ethanol plants and the implications of lifecycle analysis. *Biofuels* **2010**, *1*, 911−922.

(18) Oladosu, G.; Kline, K.; Uria-Martinez, R.; Eaton, L. Source of corn for ethanol production in the United States: A review and decomposition analysis of the empirical data. *Biofuels Bioprod. Biorefin.* **2011**, *5*, 640−653.

(19) United States Department of Agriculture, Economic Research Service, Corn Trade, http://www.ers.usda.gov/Briefing/corn/trade.htm, downloaded April, 2012.

(20) United States Department of Agriculture, Economic Research Service, Fertilizer Use and Price, http://www.ers.usda.gov/Data/FertilizerUse/ downloaded July 2011.

(21) Wang, M. Q., Haq, Z,. 2008, http://www.transportation.anl.gov/pdfs/letter_to_science_anldoe_03_14_08.pdf

(22) Duvick, D. N. *Advances in Agronomy* **2005**, *86*, 83−145.

(23) U.S. Department of Agriculture. National agricultural statistics service, http://www.nass.usda.gov/ downloaded 2011.